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TO BE MORE PRECISE:

BEIDOU, GPS, AND THE EMERGING COMPETITION IN SATELLITE-BASED PNT

A CNA report

Kevin Pollpeter

With contributions by Tsun-Kai Tsai

CNA

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To request additional copies, please direct inquiries to
Director, China Aerospace Studies Institute,
Air University, 55 Lemay Plaza, Montgomery, AL 36112

E-mail: Director@CASI-Research.ORG
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EXECUTIVE SUMMARY

The United States and the People's Republic of China (PRC) are in an emerging competition over satellite-based positioning, navigation, and timing (PNT). In 2020, the PRC completed BeiDou 3, a global navigation satellite system (GNSS) similar to the U.S. Global Positioning System (GPS). The PRC now intends to "gain a competitive edge" in satellite-based PNT by making BeiDou more accurate, integrating it into global infrastructures, and expanding its use into new domains.

This paper examines the importance of BeiDou to PRC national power. It argues that the PRC is using BeiDou as an instrument of national power to enhance its global power projection capabilities, international influence, and global commercial competitiveness. In sum, BeiDou assists the Chinese Communist Party (CCP) in achieving its goals of increasing the country's national power and ushering in a multipolar world and extends the competition between the United States and the PRC to the field of satellite PNT. If PRC plans are successful, BeiDou will enable China's military to conduct precision strikes against adversaries and could lead to the loss of international influence for the United States and expand market opportunities for PRC commerce.

BEIDOU CLOSING THE GAP WITH GPS

BeiDou is closing the gap with GPS in terms of technology and acceptance. BeiDou has more than 2 billion users and can provide navigation and positioning accuracies better than 9 meters and in some cases better than 5 meters, depending on location. The BeiDou program has benefited from a latecomer advantage that has allowed it to benchmark the performance of GPS and add functionality beyond that on GPS satellites (see Table 1).

Table 1. A comparison of BeiDou and GPS features

BeiDou Feature	GPS
Short messaging service. Allows communication between and tracking of users.	No, but emergency messaging now being offered by commercial providers.
Satellites in GEO. Satellites in GEO and IGSO mitigate the degradation of the BeiDou signal in urban and mountainous areas.	No, all GPS satellites are in MEO and no plans for future generations of GPS satellites to be placed in GEO.
Ground-based augmentation. Ground-based augmentation stations improve the accuracy of the satellite signal.	Yes.
Satellite-based augmentation. Satellite-based augmentation improves accuracy of the signal using satellites instead of ground stations.	Yes.
International search and rescue service. Allows people in distress to call for assistance.	No, but GPS IIIF satellites offering an international search and rescue service will begin to be launched in 2026.

BeiDou Feature	GPS
Intersatellite links. Facilitates communications among satellites so that instructions sent to one satellite can be sent to other satellites, improving the timeliness of satellite orbit and health information with less reliance on ground stations.	No, GPS is not equipped with intersatellite links. Although the U.S. has more ground stations to provide updates more frequently, the use of intersatellite links allows more frequent updates and better accuracies.
Laser retroreflector arrays. Laser retroreflector arrays enable better determination of satellite positions to improve accuracy of signal.	No, but GPS IIIF will be equipped with laser retroreflector arrays and will begin to be launched in 2026.
Precise point positioning. Precise point positioning enables better accuracy from a receiver when signals are perceived for extended periods of time.	Yes.
Future capability. LEO satellites. Satellites in LEO can provide stronger signals that improve accuracy and reliability.	There are no plans for GPS to incorporate LEO satellites. Commercial providers are considering LEO constellations for navigation and positioning.

Note: GEO = geosynchronous orbit; IGSO = inclined geosynchronous orbit; LEO = low Earth orbit; MEO = medium Earth orbit.

GPS REMAINS THE LEADING GNSS

GPS modernization is not standing still, however. In 2018, the Air Force signed a contract for 22 third-generation GPS satellites that are 3 times more accurate and 8 times more resistant to jamming than GPS II satellites. GPS IIIF satellites will be even more capable with new payloads, such as a redesigned Nuclear Detonation Detection System, Laser Retroreflector Arrays, a Cospas-Sarsat Search and Rescue payload, and an Energetic Charged Particles sensor. GPS IIIF also provides Precise Positioning Service to military operations and force enhancement. GPS IIIF satellites' L1C signal will be compatible with the European Union's Galileo and Japan's Quasi-Zenith Satellite System, allowing a common signal to be broadcast by up to 60 satellites, further enhancing accuracy and availability. The full complement of GPS IIIF satellites will not be available until 2033, however.

BEIDOU AS AN INSTRUMENT OF PRC NATIONAL POWER

Despite GPS's technological lead, the PRC is positioning BeiDou to become the GNSS of choice through a multifaceted program intended to promote BeiDou's dual-use capabilities across the four instruments of national power: diplomatic, information, military, and economic (DIME).

Diplomatic and information

The BeiDou program improves the reputation of the CCP domestically and the PRC internationally.

BeiDou likely improves the reputation of the CCP domestically and the PRC internationally by demonstrating that under CCP leadership, China can match the world in technological achievements. The CCP can claim that the successful completion of BeiDou

demonstrates the superiority of "socialism with Chinese characteristics" and helps legitimize the CCP's authoritarian governance model.

BeiDou's international cooperative activities build the PRC's reputation as a reliable and attractive space partner that can assist countries to develop economically, technologically, and scientifically.

BeiDou's international cooperative activities in areas such as training and education on satellite-based PNT and assistance with building infrastructure to support BeiDou help the PRC bolster its international influence, especially with countries involved in the Belt and Road Initiative. PRC activities appear to be most extensive in the Middle East. PRC cooperation with Saudi Arabia appears to be particularly strong and seems tied to the economic and military agendas of the country.

Military and security

BeiDou's PNT and communications functions provide part of the fundamental architecture for carrying out the PLA's core operational concept of multidomain precision warfare.

According to the Defense Department, multidomain precision warfare is intended to leverage a command, control, communications, computers, intelligence, surveillance, and reconnaissance network that incorporates artificial intelligence and big data to conduct joint strikes against key adversary vulnerabilities. BeiDou plays an indispensable role in multidomain precision warfare by enabling precision strike, the movement of forces, communications, and situational awareness. In this respect, BeiDou's short messaging service (SMS) function is a critical, albeit secondary, capability whose importance should not be discounted. The Chinese People's Liberation Army (PLA) is also researching the application of BeiDou across the full range of military activities, including warfighting, border defense, logistics, and mobilization.

BeiDou will provide the PRC more freedom of action to use force or threaten the use of force.

The use of BeiDou in precision strike, to guide uncrewed vehicles, and to support enabling functions such as logistics will enhance PLA efforts to deter the actions of potential adversaries and to effectively carry out strike operations if deterrence fails. BeiDou's global coverage will better enable the PLA to operate and conduct strikes globally, especially in the Western Pacific, South Asia, the Middle East, and Africa.

Conversely, the increased capabilities that BeiDou provides to the PLA could mean that efforts to deter PRC military actions will be less effective. The ability to conduct precision strikes is likely one major aspect that could increase CCP leadership's confidence in the effectiveness of military action.

Advancements in satellite-based PNT will allow the PLA to better exploit the benefits of autonomous technologies.

BeiDou's PNT functions will allow autonomous systems to guide themselves more securely and independently, and its SMS function will allow humans to issue commands to autonomous vehicles and enable autonomous vehicles to communicate among themselves in self-organizing swarm operations.

Countries' use of BeiDou in critical infrastructure could increase their dependency on the PRC.

Although it is unlikely that any country will rely solely on BeiDou for its satellite-based PNT needs, path dependencies created by countries adopting BeiDou as their primary GNSS for finance, electrical power generation, and communications infrastructure and for use with "smart cities" technologies could expose countries to PRC leverage if the PRC were to deny or degrade the BeiDou signal.

BeiDou increases PRC surveillance concerns.

The PRC's ability to monitor the movement and communications of those using BeiDou's SMS function increases PRC surveillance concerns. BeiDou's operation by the PLA suggests that the opportunities for espionage are much greater than for those systems operated by private corporations.

Economic

PRC aspires for BeiDou to replace GPS as the dominant GNSS.

Economic forces will not bring about the demise of the U.S. government–operated GPS. PRC mercantilist policies, however, can affect downstream actors that develop satellite navigation devices and applications. Although satellite navigation products and services can use signals from multiple systems, PRC mercantilist policies could help expand the popularity of devices and services manufactured and provided by PRC companies. This issue could be especially prominent in cell phone applications that use satellite navigation. An expansion of PRC companies providing satellite navigation products and services will likely mean a drop in market share for non-PRC companies, many of which are U.S. companies.

BeiDou could be more integrated with countries' national infrastructure.

Highly accurate positioning and navigation information achieved through the expansion of ground-based augmentation systems across the PRC and other countries is intended to promote the development of smart cities technologies and the use of self-driving cars and other autonomous vehicles. The more aggressive testing and adoption of autonomous vehicles of all types using BeiDou could lead the PRC to become a leader in this sector. The use of high-accuracy services may also help improve traffic management, a major element of smart cities technologies, which in

turn is a major component of China's Belt and Road Initiative, which envisions the ability to redistribute transportation flows around bottlenecks.

PRC mercantilist policies may increase the use of BeiDou in the developing world.

BeiDou's biggest economic effect will likely be greater in countries participating in the Belt and Road Initiative, in which PRC outreach is intended to take advantage of the markets of 147 countries making up two-thirds of the world's population and 40 percent of the global gross domestic product. On the other hand, the use of BeiDou in the United States will likely be limited by the dominance of U.S. companies, efforts to restrict the sale of PRC brands such as Huawei, and a ban on BeiDou ground augmentation stations being set up in the United States.

PRC-sponsored training and education is intended to increase PRC global market share.

PRC government–sponsored education and training programs contain a marketing component that is intended to advance PRC commercial interests. Training conducted by employees of PRC companies can expose potential customers to PRC products and promote the perception that PRC companies are the provider of choice for satellite PNT solutions.

RECOMMENDATIONS FOR THE U.S.

Add functionality to GPS to maintain U.S. technological lead in satellite navigation

Although not all BeiDou capabilities may need to be incorporated into GPS, the push by China to add functionality to BeiDou may create opportunities to surpass GPS. To maintain GPS's competitiveness, potential technological improvements to GPS could include the following:

- Software-upgradable satellite architectures to allow software improvements rather than hardware improvements to drive improvements in GPS.
- The addition of a high-accuracy services, such as internet-based high-accuracy services.
- Intersatellite links to allow more frequent updates.
- Expanding the constellation to geosynchronous orbit to mitigate the degradation of the GPS signal in mountainous areas and large built-up urban areas.
- Expanding the constellation to low Earth orbit to provide more accurate and reliable signals with less interference.

Develop diverse PNT solutions to provide mission assurance in the event GPS is degraded or denied

The Defense Department is developing technologies to complement GPS in the event that it is degraded or denied. These technologies include improved inertial sensors, chip-scale atomic clocks, celestial navigation, terrestrial image analysis, and magnetic navigation. None of these methods is as accurate as GPS, but when used in combination, they may provide sufficiently precise accuracies. However, according to a May 2021 Government Accountability Office report, alternate PNT sources are not prioritized within the Defense Department.

Promote GPS as an instrument of national power

The PNT competition between the United States and China means that the United States must consider not only how to best maintain its technological lead in PNT for military advantage but also how to compete with the PRC's efforts to promote BeiDou across the DIME. Strengthening the National Coordinating Office for Space-Based Positioning, Navigation, and Timing or establishing a new organization at the White House to better promote GPS as an instrument of national power—militarily, diplomatically, and commercially—could better help the United States meet the challenges of the satellite PNT competition that span across the DIME.

Conduct international GPS outreach

Establishing an office to conduct international training and education on satellite PNT with a subsidiary mission of promoting U.S. commercial interests could be one instrument for increasing U.S. influence and challenging the PRC narrative of providing a more advanced system and being a more reliable GNSS partner. An alternative to a government-run approach would be to outsource the effort to U.S. companies, possibly using the Agency for International Development, the U.S. Telecom Training Institute, or the International Development Finance Corporation.

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CHAPTER 1: INTRODUCTION

The United States and China are in an emerging competition over satellite-based positioning, navigation, and timing (PNT). Of China's major defense technology projects, the BeiDou satellite navigation program may have the most far-reaching military, political, and commercial implications. China's leaders recognize the importance of satellite navigation in creating an effective military and a competitive economy.[1]

The completion of the BeiDou program in June 2020 marks an important milestone in demonstrating the role of space power in making China a global power. The People's Republic of China (PRC) now plans to "gain a competitive edge" in satellite navigation by developing a "more extensive, more integrated, and more intelligent" BeiDou system that provides "flexible, smart, precise and secure navigation, positioning and timing services."[2] According to the PRC government, "vigorously developing China's satellite navigation industry will improve commercial efficiency, improve the lives of people, and enhance core national competitiveness, which has current and long-term strategic significance."[3]

With a budget of at least 56 billion yuan (approximately U.S. $8 billion at the current exchange rate), BeiDou is the PRC's largest space program.[4] The program involved more than 400 organizations and 300,000 personnel and resulted in the development of more than 160 key technologies.[5] Between 1994 when the program officially started and June 2020 when it was completed, China conducted 44 launches sending 4 BeiDou 1, 20 BeiDou 2, and 35 BeiDou 3 satellites into orbit.[6]

BeiDou has figured prominently in China's industrial plans and is one of China's top science and technology (S&T) programs, along with its human spaceflight and lunar exploration programs, quantum research, and commercial airliner manufacturing, among others.[7] According to Xi Jinping, BeiDou is "one of the great achievements of China's 40 years of reform."[8] The PRC government's 2022 BeiDou white paper calls it a "miracle."[9] Although BeiDou is not yet the equal of the Global Positioning System (GPS), it is closing the gap in terms of both technology and acceptance. BeiDou offers accuracies roughly similar to those of GPS, claims 2 billion users worldwide, and is widely integrated into People's Liberation Army (PLA) operations.

This paper examines the importance of BeiDou to PRC national power. It argues that the PRC is using BeiDou as an instrument of national power to enhance its global power projection capabilities, international influence, and global commercial competitiveness. In sum, BeiDou assists the Chinese Communist Party (CCP) in achieving its goals of increasing the country's national power and ushering in a multipolar world and extends the competition between the United States and the PRC to the field of satellite-based PNT.

What follows is a discussion of how the PRC is organizing to become the world leader in global navigation satellite system (GNSS). This study examines the following key aspects of this effort:

1. The importance of satellite-based PNT
2. The history of BeiDou's development
3. PRC S&T, funds, and policies supporting BeiDou
4. The BeiDou commercial industry
5. Incorporation of BeiDou into military operations
6. International cooperative activities to educate and train the developing world on BeiDou technologies and promote commercial activities
7. Implications for U.S. military and economic security and U.S. standing in the world

CHAPTER 2: BACKGROUND ON SATELLITE POSITIONING, NAVIGATION, AND TIMING

Satellite navigation systems provide three capabilities: positioning, navigation, and timing (PNT).

- ***Positioning*** refers to the ability to determine a user's location.
- ***Navigation*** refers to the ability to determine the current and a desired position.
- ***Timing*** refers to the ability to measure accurate and precise time from a standard.

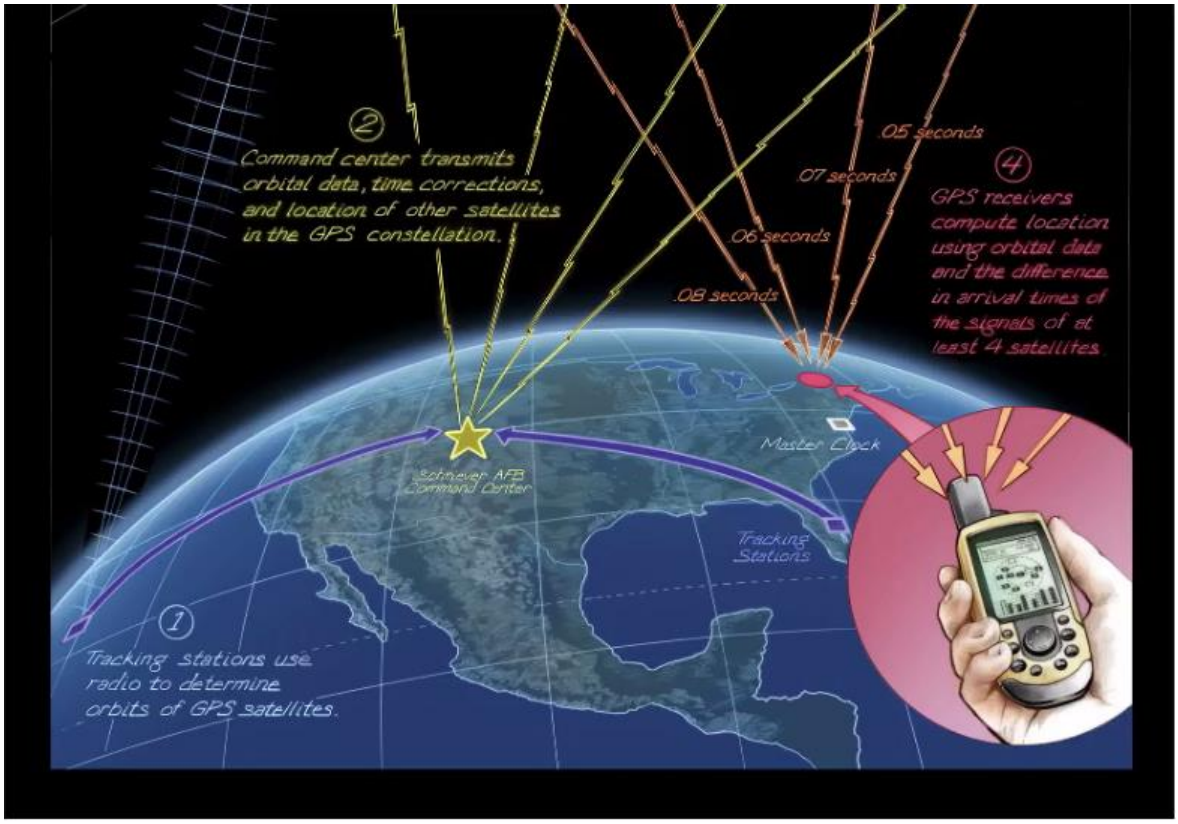
These functions rely on a process called ***trilateration***, which requires the interaction of at least three navigation satellites and a receiver. Satellite navigation receivers measure distances by the travel time of radio signals. A navigation satellite emits a signal from its orbit in space, and a receiver captures this signal and calculates its distance relative to the satellite based on the travel time of the signal. Measuring the distances between the receiver and at least three satellites allows the receiver to determine its position in three-dimensional space. Once its position is known, the receiver can locate the distance to other destination points. PNT does not have to rely on just three satellites, however. Receivers can process signals from multiple satellites. In fact, using more than three satellite signals improves the accuracy of PNT.

Because timing is central to this process, satellite navigation systems require extremely precise and accurate instruments to measure the time that it takes for the radio signal to reach a receiver. These instruments are atomic clocks, and they are so accurate that they may lose or gain only a second over millions of years. The atomic clocks on board GPS satellites, for example, can determine time to within 100 billionths of a second. As a result, the precision of atomic clocks used by a satellite navigation system to a large extent determines the accuracy of the positioning information that the system can provide. The timing information provided by these clocks can also be used to synchronize a variety of functions and systems, as discussed further in the following sections.

SATELLITE NAVIGATION SYSTEMS

Satellite navigation systems are composed of three segments: a ground segment, a space segment, and a user segment that makes the trilateration process happen (see Figure 1).

Figure 1. How satellite-based PNT works



Source: Smithsonian Institution, "How Does GPS Work?" https://timeandnavigation.si.edu/multimedia-asset/how-does-gps-work.

Ground segment

The ground segment consists of a master control station, uplink stations, and monitoring stations that help users know the position of navigation satellites in orbit. These stations form a network of ground facilities that track the satellites, monitor their transmissions, perform analyses, and send commands and data to the constellation.

Space segment

The space segment consists of satellites in orbit. These satellites are made up of a platform and instruments. The platform includes onboard systems required for the satellite to operate, such as a computer and a power supply. The instruments include the atomic clocks and radio transceivers required for the satellite to perform PNT functions.[10]

User segment

The user segment consists of receivers that capture the satellite-emitted signals, calculate PNT, and display positioning and navigation information to the user.

SATELLITE NAVIGATION APPLICATIONS

Satellite navigation systems underpin numerous applications and are built into the infrastructures and tools relied upon by military, civil, and commercial users. A common refrain in the literature on satellite navigation is that its uses are limited only by the human imagination.[11] Indeed, satellite navigation has transformed from a niche military capability to a vital part of national infrastructure that helps power the modern economy.

Military

Satellite-based PNT first gained prominence for its military applications. The U.S. military launched the first navigation satellite, Transit, in 1959—less than two years after Sputnik. Transit became fully operational in 1968 with a constellation of 36 satellites and operated until 1996, when it was replaced by GPS. The original purpose of Transit was to assist in the navigation of ballistic missile submarines.[12]

After GPS was made fully operational in 1995, precision bombing, first promised in World War II, finally became a reality, and its use increased over the following years. For example, GPS-guided munitions accounted for just 3 percent of all munitions expended in Operation Allied Force conducted in 1999. During the first three months of Operation Enduring Freedom in 2001–2002, that number had risen to 32 percent. In the 29 days of the initial 2003 invasion of Iraq, precision-guided munitions of all types made up 68 percent of all munitions expended (see Table 2).[13]

Table 2. Precision-guided munition use from Desert Storm to Iraqi Freedom

Operation	Munition Type	Number	Percentage
Desert Storm 1991	Unguided	245,000	92
	Laser-guided/Electro-optical	20,450	8
	GPS	≥35	>0
Allied Force 1999	Unguided	16,000	66
	Laser-guided/Electro-optical	7,000	31
	GPS	700	3
Enduring Freedom 2001–2002	Unguided	9,000	41
	Laser-guided/Electro-optical	6,000	27
	GPS	7,000	32
Iraqi Freedom 2003	Unguided	9,251	32
	Guided (all types)	19,948	68

Sources: Morris et al., *A Day Without Space: Economic and National Security Ramifications*, p. 26; Tyler Rogoway, Operation Secret Squirrel Saw B-52s Rippling Off Cruise Missiles at Iraq 25 Years Ago," Jalopnik, Jan. 18, 2016, https://jalopnik.com/operation-secret-squirrel-saw-b-52s-rippling-off-cruise-1753637282.

Civilian

With the U.S. government's decision to allow civilian access to the GPS signal with military-grade accuracies in 1990, the use of GPS for civil and commercial applications proliferated. Satellite-based PNT now underpins the working of the modern economy. Satellite-based PNT is ubiquitous, and without it, many of the activities that we take for granted would not be possible. Its most recognized popular application is its use in mapping applications to help us travel from one location to another, but commercial applications for satellite-based PNT are numerous and varied. Satellite PNT can assist with tracking vehicles to better manage the dispatching of drivers and assist in fleet management by helping to schedule maintenance and provide better routing to save on fuel costs.[14] Farmers use satellite navigation to aid in plowing and harvesting their fields and applying fertilizer, pesticides, and herbicides, as well as to create maps of yield output and improve farming routes.[15] Ride hailing and delivery apps rely on satellite navigation to reach their customers and for customers to know where their rides or deliveries are.

Critical infrastructure

Perhaps the most important and least recognized function of satellite navigation is as an element of national infrastructure. Navigation satellites provide critical support to power grids, stock markets, transportation systems, and information and communications networks. The electrical power generation industry uses the timing function of navigation satellites to synchronize power plant generators, share power with adjacent grids, and identify the location of short circuits.[16] And although the loss of the satellite navigation signal would not cause the loss of the power grid, it would make electrical power generation less efficient and more expensive.[17]

The financial industry also uses the timing function. The New York Stock Exchange, for example, uses GPS to time-stamp stock trades, and banks and credit card companies use it to time-stamp withdrawals from ATMs and purchases.[18] Satellite navigation is also used to synchronize cell phone communications so that multiple customers can share limited bandwidth.[19] Banks and other financial institutions use timing signals from navigation satellites to process billions of financial transactions efficiently and in order. Wireless telephone service providers and other data networks use satellite navigation to keep base stations synchronized, which then allows cell phones to efficiently use limited radio spectrum.[20]

CHAPTER 3: SATELLITE NAVIGATION SYSTEMS

The United States, China, Russia, and the European Union (EU) operate the four GNSS. In addition to these global systems, two regional navigation satellite systems operated by India and Japan provide PNT services to areas surrounding those countries. GPS was the first GNSS and has long been the standard and most widely used. BeiDou is the most recent of the four GNSS. Each of these systems is discussed in the following sections.

GLOBAL POSITIONING SYSTEM

GPS has more users worldwide than any other satellite navigation system. The GPS constellation consists of at least 24 satellites and in recent years has used as many as 31 satellites in medium Earth orbit (MEO) at an altitude of 20,200 kilometers.[21] The first GPS satellite was launched in 1978, and the complete constellation entered into full operation in 1995. GPS initially provided a military-grade signal and a degraded civilian signal. This bifurcation ended in 2000, and now all users receive the more precise signal originally intended for military use. With this change, GPS now typically provides real-time positioning accuracies to within 4.9 meters for smartphone users, although this accuracy may be degraded by obstacles, such as buildings.[22]

GLONASS

Russia's GLONASS was completed in 1995 and consists of 24 satellites in MEO operating at an altitude of 19,100 kilometers. In the late 1990s, as Russia's economy faltered, the constellation fell into disrepair, but under President Vladimir Putin the constellation was restored to full capacity in 2011.[23] The GLONASS constellation is positioned to provide better accuracies at northern latitudes to better cover Russia and provides accuracies of 5 to 10 meters.[24]

GALILEO

Galileo has been operational since 2016 and is owned and operated by the EU. The EU launched the first two Galileo satellites in 2011, and it now operates a constellation of 23 satellites that operate at an altitude of 23,222 kilometers.[25] According to the European Space Agency, Galileo is the only civilian-operated GNSS and was developed to establish an independent capability separate from other GNSS.[26] Galileo can achieve accuracies of 2 to 3 meters.[27]

BEIDOU

According to the 2016 BeiDou white paper, the development goal of the BeiDou program is to build a world-class navigation satellite system to meet the needs of China's national security and economic and social development and "provide continuous, stable, and reliable services for global users."[28]

Key organizations

The BeiDou program appears to be managed at the highest level by the China Satellite Navigation Commission (中国卫星导航系统委员会).The organization has been likened to a leading small group, which implies that its role is to take into account and coordinate the interests of various stakeholders, likely numerous organizations responsible for policy, oversight, program management, and technology development from the military, government, defense industry, and academia.[29] Although the military was responsible for leading the research and development (R&D) effort and operation of BeiDou, State Council ministries and subordinate bureaus have been responsible for the management of industrial partners, oversight and approval of BeiDou's development, and budget allocation. Reflecting the military nature of the BeiDou program, the commission's top leader is a military officer.[30]

The China Satellite Navigation Office (CSNO; 中国卫星导航系统管理办公室) is responsible for the day-to-day management of the BeiDou program. CSNO appears to report to the PLA's Surveying and Mapping Bureau, now under the Strategic Support Force.[31] Since its establishment in the early 2000s, the CSNO has been in charge of the general management and administration of the program and its links to other entities, including defense industry contracts, associated applications, and general industrial implementation of the program.[32]

BeiDou's development

PRC officials assert that BeiDou was completely developed by China.[33] BeiDou has followed a "three-step" development plan involving three generations of satellite constellations. Step 1 began in 2000 and involved the launch and operation of BeiDou 1, a regional radio determination satellite service. Step 2 began operation in 2012 and was a more advanced regional system. Step 3 began in 2020 and is a global service.

BeiDou 1

BeiDou 1 was established in 2000. The technologies in BeiDou 1 differed substantially from those of other navigation satellite systems. Whereas other navigation satellite systems use a passive system, BeiDou 1 used an active system called radio determination satellite service (RDSS). This system was composed of three satellites in geosynchronous orbit (GEO) with one acting as a backup satellite, at least one ground station, and receiver-transmitters that communicated with each other.[34] These receivers both picked up satellite signals and sent a signal back to the satellites, which then forwarded it to the ground station. The ground station then calculated the position of the receiver and communicated these data to the receiver. BeiDou 1 provided two-dimensional positioning that could achieve accuracies of up to 20 meters and supported a short messaging service (SMS) for messages of up to 120 characters.[35]

BeiDou 2

BeiDou 2 initiated China's efforts to establish a modern navigation satellite system through the development of a passive system similar to GPS. BeiDou 2 began operations as a regional system on December 27, 2011, and was composed of 14 satellites in GEO, inclined geosynchronous orbit (IGSO), and MEO covering 94.6 percent of the Asia-Pacific region.[36] BeiDou 2 retained the SMS function of BeiDou and may have been able to provide users with the location of other nearby users.[37]

BeiDou 2 offered a positioning accuracy of 10 meters, velocity accuracy of 0.2 meters per second, and a timing accuracy of 10 nanoseconds. An authorized service for military and government use provided more secure positioning, velocity, timing, and communications services at higher integrity. BeiDou 2 satellites had an expected operational life of eight years.[38]

BeiDou 3

BeiDou 3 is a passive system similar to GPS but with key differences. The planned constellation consists of satellites in three orbits: 25 in MEO, 5 in GEO, and 5 in IGSO. Currently, the BeiDou constellation consists of 45 satellites made up of 15 BeiDou 2 satellites and 30 BeiDou 3 satellites.[39] The five GEO satellites provide the SMS and, like other communication satellites, are placed in that orbit to provide the best global coverage. The five IGSO satellites are intended to reduce the "urban canyon" effect, whereby satellite signals are degraded or lost in dense urban areas.[40] BeiDou 3 is optimized to provide the best coverage over the Asia-Pacific, with the number of visible satellites reaching between 12 and 16.[41] The PRC government states that BeiDou can provide navigation and positioning with accuracies better than 9 meters but that some users may receive accuracies of 5 meters or even 2 to 3 meters, depending on location.[42]

BeiDou's features

BeiDou 3 offers several features.

Short messaging service

BeiDou 3 has two types of messaging services. A regional SMS is offered to users in China and surrounding areas that can send messages containing up to 1,000 characters. A global SMS is offered to users outside of China and its surrounding areas that can send messages containing up to 40 characters.[43] BeiDou 3 also has increased bandwidth that expands the number of users from 500,000 to 5 million.[44] BeiDou's SMS function also has location tracking that allows users to know not only their location but also the location of others on the BeiDou network.[45]

International search and rescue service

Six BeiDou 3 satellites provide an international search and rescue service that allows users to send or receive distress messages for maritime, aviation, and land users globally.[46]

Satellite-based augmentation service

BeiDou's satellite-based augmentation service is similar to the U.S. Wide Area Augmentation System operated by the Federal Aviation Administration to provide enhanced navigation and positioning accuracies to civil aviation. The system uses a series of ground stations that enhance the BeiDou signal. Those signals are then relayed to BeiDou's communication satellites in GEO, which then broadcast them to aircraft.[47]

Ground-based augmentation service

The PRC is building a network of ground-based augmentation stations (GBAS) around China and internationally that improve the accuracy of the BeiDou signal. GBAS are a way to improve the accuracy of the satellite signal and are commonly composed of one or more accurately surveyed ground stations, which take measurements concerning the GNSS, and one or more ground-based radio transmitters, which transmit the information directly to the end user. According to the PRC government, in 2020 there were 3,000 GBAS in China that can achieve real-time meter-level, decimeter-level, and centimeter-level accuracies.[48]

Precise point positioning service

BeiDou also offers users a precise point positioning service that provides positioning accuracy of 20 centimeters horizontally and 35 centimeters vertically with a convergence time of 15 to 20 minutes.[49] Precise point positioning can be accomplished using one GNSS receiver that monitors a GNSS signal over a period of time. More precise measurements can be achieved by using dedicated software that analyzes the GNSS signal. The extended time required to analyze the signal means that precise point positioning is not useful for real-time navigation but can be used for more stationary applications such as surveying and mining.[50]

BeiDou's precise point positioning function is provided by the system's three GEO satellites and uses the GPS signal to provide the service. It is available only in China and surrounding areas. A global capability is planned.[51]

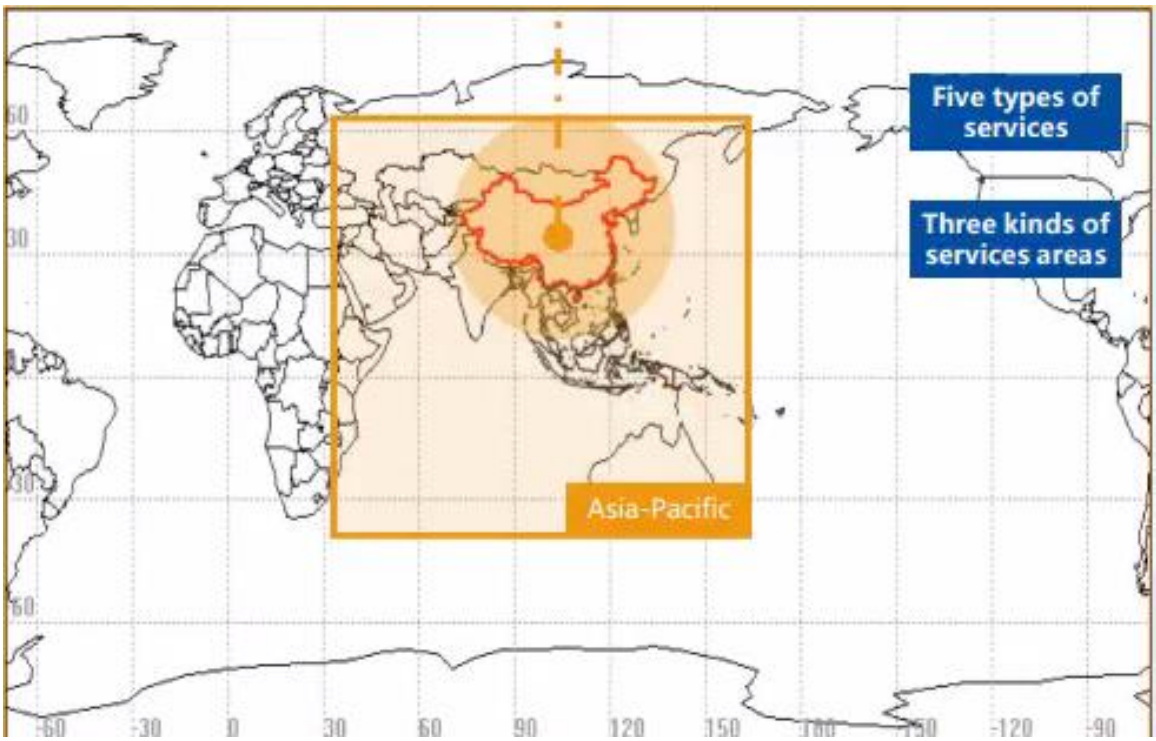
Table 3. BeiDou compared with other global navigation satellite systems

	BeiDou 3	GPS	Galileo	GLONASS
Constellation	45 satellites (7 in GEO, 10 in IGSO, 28 in MEO)	31 satellites (all in MEO)	28 satellites (all in MEO)	24 satellites (all in MEO)
Accuracy	<9 m	5 m	≤2 m	5–10 m
Military signal	Yes	Yes	No	Yes
SMS	1,000 characters in China and surrounding areas	No	No	No

Sources: Li Liu et al., "Improved Design of Control Segment in BDS-3," *Navigation* 66, no. 1 (2019), https://onlinelibrary.wiley.com/doi/abs/10.1002/navi.297, p. 38; European GNSS Agency, *Open Service Definition Document,*

May 2019, https://galileognss.eu/wp-content/uploads/2020/08/Galileo-OS-SDD_v1.1.pdf; "GLONASS Performances"; "About GLONASS."

Figure 2. Coverage area of BeiDou's satellite-based augmentation system, precise point positioning, and regional short messaging service



Source: Shen and Geng, "Update on the BeiDou Navigation Satellite System (BDS)."

Program budgets

Funding figures indicate that BeiDou is one of the largest space projects undertaken by China. According to unofficial sources, by the end of 2012, China had invested more than 16 billion yuan (U.S. $2.57 billion) in BeiDou and planned to allocate a further 40 to 50 billion yuan (U.S. $6.41 to U.S. $8.02 billion) from 2013 to 2020 for a total of 56 to 66 billion yuan (U.S. $8.9 billion to U.S. $10.57).[52] In addition, the country planned to invest 5 billion yuan (U.S. $810 million) in a BeiDou industrial park.[53] According to a 2020 article, the total cost of the program from 1996 to 2020 was U.S. $12 billion or around 83.5 billion yuan.[54] In comparison, an official budget figure for China's human spaceflight program from 1992 to 2012 put the budget at 40 billion yuan, or potentially more than 40 billion less than BeiDou for a similar time period.

Future

The PRC government states that in the future, BeiDou will be further integrated with 5G, mobile communications, big data, and the internet. By 2025, the PRC will begin building a low

Earth orbit (LEO) augmentation to improve the speed, reliability, and accuracy of the signal. By 2035, the PRC plans for BeiDou to be "more ubiquitous, integrated, and intelligent" and capable of providing "core support" to the development of autonomous vehicles and new-generation communications. The intention is to create a system that can provide accuracies down to 2 millimeters globally. The PRC is also investigating other capabilities, such as quantum navigation, underwater navigation, and deep space navigation.[55]

REGIONAL SYSTEMS

Quasi-Zenith Satellite System

Quasi-Zenith Satellite System (QZSS) is a four-satellite navigation satellite system operated by Japan that became operable in 2018. QZSS was established as a complementary system to work with GPS to provide better coverage of Japan.[56]

Navigation with Indian Constellation

Navigation with Indian Constellation (NavIC) is a seven-satellite navigation system operated by India that became operational in 2018. U.S. refusal to provide GPS during the 1999 Kargil war between India and Pakistan reportedly drove the development of NavIC.[57] NavIC provides service to India and surrounding areas out to 1,500 kilometers and can provide accuracies of 20 meters.[58]

CHAPTER 4: HISTORY OF CHINA'S SATELLITE NAVIGATION EFFORT

PRC leaders' interest in and support of satellite navigation programs evolved in step with their perceptions of GPS and its strategic implications. Observing the development of GPS in the 1980s, some scientists and military officers believed that as long as China relied on GPS, the U.S. military's ability to degrade or deny the GPS signal to the PLA presented a security threat. According to Major General Yuan Shuyou, director of the General Staff Department's (GSD's) Surveying and Mapping Bureau at that time, "If there is a change in international relations or a war breaks out, Sino-US relations will be affected, and the United States will shut down the GPS signal covering China, and the consequences will be unimaginable."[59] According to another PLA officer, "If the United States cuts off coverage, China could be paralyzed."[60]

According to PRC media, the need for an independent satellite navigation system grew more urgent after the PLA allegedly experienced the interruption of its GPS signal during exercises in 1996, a time when cross-strait tensions ran high when the PLA fired ballistic missiles in the waters near Taiwan.[61] Despite these concerns, the program was hindered by resource constraints and slowed by leaders who did not see a need to commit resources to build a system that would replace the free GPS service.

By the 2000s, however, circumstances had changed. The government had the means to fund large technology development programs, and PRC leaders grew convinced of the need to end China's reliance on GPS. Against this backdrop, PRC experts began to see BeiDou as necessary for the PLA's transition to fighting "local wars under informatized conditions."[62] According to PLA doctrine, victory in these conflicts depends on achieving information dominance. In other words, the PLA viewed victory as depending on the ability to use information, of which satellite PNT data are a critical element, and to deny information to an enemy.[63]

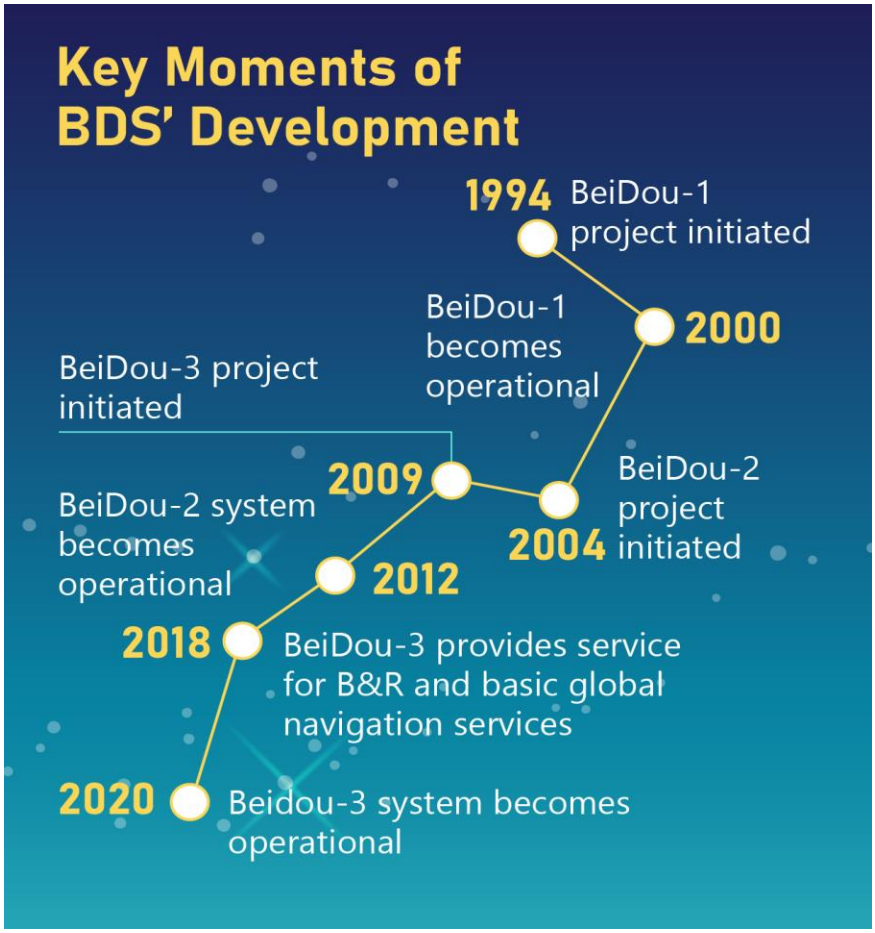
As the PLA's missions have evolved since the mid-2000s, an independent satellite navigation system has grown even more important to defense modernization. Such a system could support the PLA's transformation into a force capable of fighting wars in distant theaters and employing long-range precision-guided munitions. Assured autonomous PNT capabilities could enhance the PLA's capacity to engage an adversary's naval forces farther from China's shores, using precision-guided capabilities such as long-range antiship ballistic and cruise missiles.

China's leaders had also begun to see the commercial potential of satellite navigation technologies. Since at least 2006, experts have represented BeiDou as basic technological infrastructure upon which new and strategic emerging industries should develop.[64] The goal, in this view, is to foster commercial firms to research, develop, and manufacture across the entire satellite navigation industrial chain, from chip technology to receivers to services for consumers. These motives introduced new considerations, including civil-military integration, commercial

feasibility, and industrial development, and resulted in China's State Council designating the BeiDou program a national infrastructure project and including it among the 16 megaprojects identified as priorities in the important 2006 Medium and Long-Term Plan for Science and Technology Development.

The next sections detail the history of the BeiDou program from inception to BeiDou 2. Unfortunately, no historical information appears to be available on the development of BeiDou 3.

Figure 3. BeiDou development timeline



Source: Adapted from "China Achieves Key Independent Tech with Full Global Service of BeiDou," *Global Times*, July 31, 2020, https://www.globaltimes.cn/content/1196264.shtml.

FIRST PROPOSALS FOR BEIDOU: 1983–1986

The PRC's efforts at satellite navigation began with the Lighthouse (灯塔) program, conceived for the PLA Navy (PLAN) by noted rocket scientist Qian Xuesen in the late 1960s. Having observed the U.S. Navy's Transit system, leaders believed a positioning signal from space would strengthen the PRC's nuclear deterrent. Little information is available on the Lighthouse

program, but it is known that it began at the Fifth Academy, later known as the China Academy of Space Technology (CAST), before being canceled during Deng Xiaoping's deprioritization of defense spending in the 1980s.[65]

In 1983, a group led by CAST scientist Chen Fangyun proposed a two-satellite RDSS constellation.[66] An electronics expert, Chen was among four elite scientists who would later found the 863 Program, a major PRC technology funding program initiated in 1986.[67] Chen argued that a domestic satellite navigation capability was necessary to reduce the PRC's reliance on foreign systems, serve Deng's "four modernizations," and spur economic development.[68] The group argued that this system was feasible given domestic technical capacity at the time and that it could be completed quickly.[69]

Although years had passed since the end of Lighthouse, at least some in the PLA had not lost interest in satellite navigation. Bu Qingjun, the director of the GSD's Surveying and Mapping Bureau, had also concluded that the PRC needed an independent satellite navigation capability. Attending a conference in Washington, DC, in 1985, Bu heard a U.S. military officer explain that the U.S. could deny access to GPS during times of conflict. An alarmed Bu reported that "this was all discussed openly at the conference. After I understood this, I felt that if we relied on this we would be at the control of others." Upon his return, Bu wrote to his leaders recommending the development of an independent system but provided no specific research plan.[70]

Shortly after returning to China, Bu attended another conference, where he heard Chen Fangyun give a speech titled "Using Two Satellites to Solve the Ground Positioning Problem."[71] Seeing in this proposal a means to building the system he sought, Bu approached the deputy director for the Commission for Science and Technology and Industry for National Defense, Shen Rongjun. Bu, Chen, and Shen then formed the nucleus of a group to advocate for a satellite navigation program.[72]

In March 1986, as the State Council was adopting the 863 Program, Bu requested that top leaders authorize research into the two-satellite program proposed by Chen. A month later, the government convened a feasibility meeting attended by participants from the ministries of Railways and Transportation and the bureaus of Telecommunications and Forestry. Most rejected the proposal, stating that GPS made a PRC system unnecessary. They also doubted whether the domestic space industry was technically capable of building the system and whether the government could afford to fund the project.[73]

After continued discussions, Bu convinced detractors of the strategic and national security interests in developing an independent system. The navigation satellite proposal team applied for funding and obtained approval for a preliminary research project.[74]

FEASIBILITY STAGE: 1986–1994

Having secured modest funding for initial research, Bu's team began its work defining the system and demonstrating its feasibility.[75] The team envisioned a constellation of two satellites providing a signal over China, a system far more modest in scale and performance than GPS. As prominent space engineer Sun Jiadong explained, BeiDou "was based on China's own requirements and economic potential. At that time, China had just begun to open up and its economic potential was insufficient. In addition, at that time we did not need to design a global system."[76]

In 1986, the GSD Surveying and Mapping Bureau, PLAN, Ministry of Aviation and Aerospace, Ministry of Machinery and Electronics, and Oceanic Bureau began research with a view to developing a demonstration project. During this early stage, several organizational and institutional factors hindered their work. First, research was scattered across too many organizations, each acting independently and too focused on near-term issues. Second, these organizations failed to benchmark their R&D plans against GPS. Finally, they ignored the potential commercialization of BeiDou.[77] In spite of these challenges, researchers developed 17 technologies for testing between 1986 and 1994. By 1989, the project had undergone three feasibility assessments and demonstrated a theoretical and technological basis for its continuation.

In September 1989, the GSD Surveying and Mapping Bureau performed a first demonstration and test of the system using two DFH-2A communications satellites already in orbit.[78] The test reportedly established that the system could provide accuracies comparable to the public GPS signal.[79] The successful demonstration marked a turning point that positioned the Survey and Mapping Bureau to advocate for a full-scale test program. By 1994, the team had completed preliminary feasibility work and successfully conducted a ground test of the satellite and a tabletop test of the payload.[80] This work resulted in the project being formally approved in 1994.[81]

PLANNING AND DESIGN, PRELIMINARY RESEARCH, AND MANUFACTURING: 1995–1998

The approval of the project in 1994 did not mean that the project would proceed smoothly, however. In 1995, the State Council endorsed the BeiDou project for inclusion in the Ninth Five-Year Plan that governed the period from 1996 to 2000 but could not guarantee sufficient funding for it to move beyond preliminary research. Bu told the State Council that the project was ready to enter the next stage of R&D and that continuing to limit the activities to preliminary research would effectively end it. He proposed instead that resources allocated to backup satellites for another program be redirected toward the BeiDou 1 demonstration. The State Council gave its formal approval to this approach, and technical work on developing and building the satellites began.[82] According to BeiDou Deputy Chief Designer Li Zuhong, "If the BeiDou satellite project

plan had been stranded at that time, then our current satellite navigation technology level may have been set back by at least 10 years."[83]

Motivation for prioritizing BeiDou may have increased when the PRC fired missiles into areas surrounding Taiwan in 1995 to protest what the PRC viewed as Taiwan President Lee Teng-hui moving away from a One China Policy and in 1996 to try to influence the presidential elections in Taiwan. According to the *South China Morning Post*, a retired senior PLA officer alleged that some of the missiles fired around Taiwan did not hit their intended target areas because of disruptions in the GPS signal instigated by the United States. According to this officer, "It was a great shame for the PLA . . . an unforgettable humiliation. That's how we made up our mind to develop our own global [satellite] navigation and positioning system, no matter how huge the cost. BeiDou is a must for us. We learned it the hard way."[84] Reflecting on the success of the BeiDou program, retired PLA General Xu Guangyu has also stated that with BeiDou, "there is no chance now for the United States to use its GPS to interfere in our operations at all."[85]

FINAL R&D STAGES: 1998–2000

Having received formal approval, the team set a timetable for the first satellite launch: "strive for 1997 and guarantee 1998" (保八争七). The group also adopted as a slogan "precision accuracy, independent innovation" (导航精度要高，要有自己的创新), a theme that would be reiterated throughout the next decade. Even though overall spending on space accelerated during this period, for most of the 1990s, China's overall space activities focused on the human spaceflight program, to which satellite navigation took a backseat.[86]

Because of this lower status, the program faced hurdles stemming from constraints on funding and personnel. First, proponents of other programs proposed moving responsibility for BeiDou from CAST to the smaller Shanghai Academy of Space Technology. They argued that CAST was the prime contractor for the human spaceflight program and overall priority should be given to human spaceflight activities. Bu and Chen lobbied to keep the BeiDou program in Beijing, however. Following their efforts, the program finally settled into a permanent home in Beijing's "Space City" and got funding approval for its ground center in 1997.

A second hurdle for the program to overcome was the lack of skilled personnel. To build a team, Bu sought PhD students at the Harbin Institute of Technology, a prestigious S&T university that was a major supplier of graduates to the defense industry. After 1992, however, when Deng Xiaoping had made his historic tour of southern China and proclaimed that "to get rich is glorious," many graduates sought employment in the private sector, especially with foreign companies and joint ventures. Unable to compete with private-sector salaries or housing opportunities, he was able to recruit only four or five undergraduates.[87]

Despite these difficulties, the team was able to address several technology challenges during the research stage. First, they incorporated the capability required to transmit messages of

up to 120 characters into the design. To minimize risk, they adopted a proven concept in use on China's communications satellites.[88]

Second, the team determined that the system needed three-axis stabilized satellites instead of the spin-stabilized platforms then in use. This system would allow the satellites' antennas to remain pointed at Earth. They also increased the power requirement on the antenna, changed its frequency, and adopted measures to address internal electromagnetic interference.[89]

Third, the Surveying and Mapping Bureau needed a powerful computer at the ground segment to digitize geospatial data. The team evaluated the PRC's Yinhe supercomputer but assessed that it was not powerful enough for the application and instead purchased a foreign supercomputer.[90]

Fourth, in 1997 a frequency overlap with a Russian satellite required changing BeiDou's frequency. Finally, scientists determined that the system's navigation response standard could not exceed 5 seconds. Difficulties in meeting this last requirement delayed the launch of the first satellite from the 1998 target to 2000.[91] In fact, construction of the first BeiDou 1 satellite did not begin until early 1997, with the transition from the prototype R&D stage to the final R&D stage occurring in 1998.[92]

LAUNCH AND ORBITAL TESTING STAGE: 2000–2003

In late 2000, the first two BeiDou 1 satellites were launched. After the satellites launched from the Xichang Satellite Launch Center, the PLA's General Armament Department took over the operation of the experimental system, using facilities in Xi'an and Beijing. After this experimental system began operating, the China National Space Administration published the country's first space white paper, which listed building an independent satellite navigation system as an objective. The document outlined a phased approach to this goal with measures to develop a related domestic applications industry.[93]

ORBITAL MANAGEMENT STAGE: 2003–2004

With the orbit of a third backup satellite in 2003, the system went from experimental to operational and began to support civilian applications. With an overall R&D cost of 1 billion yuan,[94] the central government regarded BeiDou 1's development and operation as successful and the applications it supported as bringing important benefits to industry, agriculture, forestry, fisheries, transportation, and disaster response.[95]

BEIDOU 2: 2004–PRESENT

A confluence of new needs and circumstances set the stage for the decision to build a more capable second-generation national satellite navigation system. Feasibility studies for such a system had begun as early as 1997. Over the following years, several policies encouraged satellite

navigation system development and applications, leading to the formal adoption of BeiDou 2 in 2004.

Proposals for a second-generation system

By 2000, a rapidly growing economy put the means to a more capable satellite navigation system within reach. When Hu Jintao came to power in 2002, the central government no longer faced the tight budget constraints that limited his predecessors' activities. Decades of sustained rapid economic growth and tax reforms concentrated revenues at the center. Technology development programs would become one destination for the wealth accumulating in the central government's coffers. Political support for large defense programs was also strong. Within this favorable political setting, in 2004, the central government formally adopted a policy to build BeiDou 2.

BeiDou 2 was to address some of the technical limitations of BeiDou 1. BeiDou 2 would be a more rapid, precise, and versatile RNSS system to meet both military requirements and civilian needs. Perhaps recognizing how funding shortages constrained the BeiDou 1 program, six Chinese Academy of Sciences (CAS) academicians sent the State Council a document, *Suggestions for Improving BeiDou Navigation System Applications*, in 2004 advising that the development of a satellite navigation system required the full support of the government. These suggestions are said to have attracted the attention of the State Council. Subsequently, the Satellite Application Work Committee requested comments on the opinions from relevant organizations.[96]

The academicians' opinions appear to have prompted the National Development and Reform Commission, which has administrative and planning control of China's economy, and the Commission on Science and Technology for National Defense, a high-level organization responsible for defense procurement, to jointly issue their *Notice on Works of Accelerating and Promoting the Application of the BeiDou Navigation System* the following year. This notice designated the constellation a "national infrastructure" and outlined a revised timetable that included full utilization of the system's demonstration project. The document also provided for policy measures that would support the commercialization of receiver technology and the development of a local receiver manufacturing industry.[97]

The importance of satellite navigation was reinforced when the Ministry of Science and Technology issued the *National Medium- and Long-Term Program for Science and Technology Development (2006–2020)* in 2006. This document designated 16 (13 unclassified and 3 classified) technology programs as megaprojects, including Earth remote sensing, lunar exploration, and human spaceflight as unclassified projects. The inclusion of BeiDou 2 as one of the three classified projects meant that BeiDou would receive plentiful funding and other resources but with a secrecy that demonstrated the inherent military value of satellite navigation.[98]

By the time BeiDou 1 was completed, it was apparent that restricting the system to a regional service would limit its military and commercial applications. China's trade and security interests had expanded across the globe, and in 2004, the PLA had been tasked with carrying out the "New Historic Missions," which, in part, required the PLA to defend China's interests in the "far seas."[99]

According to Beijing University of Aeronautics and Astronautics scholar Li Chengzhi, however, as late as 2008, top leaders still had not reached a final decision on whether BeiDou 2 would remain a regional program or expand to provide global coverage.[100] In 1998, CAS academician Wei Ziqing argued that the development direction of China's space and weapons technology required that it possess a GNSS, and in 2002, CAS academician Tong Kai argued that China should develop a regional system that could be expanded to a global system when the needs and resources of the country permitted.[101] However, other sources suggest that PRC decision-makers were seriously considering the program as culminating in a global system as early as 2007.[102] In 2007, China registered 36 slots for BeiDou with the International Telecommunications Union,[103] and a 2007 *International Aviation* article reported that China would establish a system with 30 satellites in non-GEO orbits and 5 in GEO orbits.[104] The official announcement that BeiDou 2 would provide global coverage did not come until 2009, however. An executive meeting of the State Council approved the project when it issued the *Implementation Scheme of the Major Science and Technology Project of China's Second Generation Navigation Satellite System*.[105]

Between 2007 and 2012, 16 BeiDou 2 satellites were launched to form a constellation that formally began providing a regional service in 2012. An additional BeiDou 1 backup satellite was launched in 2007 to continue service through the operationalization of BeiDou 2. Of these, a BeiDou 2 satellite launched on April 14, 2007, appears to have been important. That satellite carried a new atomic clock said to have been independently developed by China and marked an entirely new development phase for BeiDou.[106]

The new system has also experienced technical problems and weaknesses. The first BeiDou 2 satellite reportedly had a clock problem. The second, launched in 2009, ceased transmitting and began to oscillate uncontrollably.[107] In 2007, the system experienced crippling electromagnetic interference, which threatened to disable the constellation and disrupt the entire program.[108] Interference posed challenges throughout the early construction of the system, causing signal degradation and weakening performance. Researchers at the Satellite Navigation Office of the National University of Defense Technology solved some of these problems by creating an electromagnetic shield to protect satellite components.[109]

Moreover, the performance of BeiDou 2 was considered suboptimal. According to one source, BeiDou 2 was more susceptible to jamming than GPS because of its weaker signal.

Weaknesses in BeiDou 2's pseudorange positioning (the approximate distance between a satellite and a receiver) also hindered the navigation and positioning signal that BeiDou 2 provided.[110]

BeiDou 2 R&D

Information on the research, development, and acquisition (RDA) process for BeiDou 2 is scarce. Feasibility studies reportedly began on BeiDou 2 in early 1997 at the same time that construction began on the first satellite for BeiDou 1. CAST's Xi'an Branch established several research institutes and laboratories to manage the development of components. These included a research institute for satellite communications and navigation technology, a timing and frequency laboratory, a navigation task processing laboratory, and a special technology laboratory for critical technology breakthroughs. In addition to these organizations, the Xi'an Branch office's Payload Department established a Navigation Satellite General Office to oversee the overall effort.[111]

CAST's Xi'an Branch office did not conduct any preresearch for BeiDou 2, so during the preliminary R&D stage, the office had to conduct design, manufacture, and testing in parallel and resolve technical issues during the final R&D stage. In meeting this challenge, the Xi'an Branch organized innovation teams made up of senior, midlevel, and junior staff, some of whom had worked on BeiDou 1, described as the "brain trusts" for innovation. These teams understood the development goals of BeiDou 2, foreign systems, customer requirements, and the planning concept for BeiDou 2.[112]

Possibly sometime after 2004, the GSD Satellite Navigation and Positioning Main Station conducted surveys of the entire military, including command, operational, equipment, school, and research units, to see how they used satellite navigation. The results of this survey were used to develop the requirements for BeiDou 2. The survey resulted in the first-ever proposal for a system enabling a commander to know the precise location of units and individual soldiers. After BeiDou 2 was introduced into the field, personnel from the GSD Satellite Navigation and Positioning Main Station also assisted troops in using BeiDou. After this introduction, BeiDou was described as being a part of a "level three command and control network," which referred to command and control systems below the military region level.[113]

ATOMIC CLOCKS

Perhaps the most important technology innovation for the BeiDou program was the development of an atomic clock precise enough to provide accuracies to at least 10 meters.[114] Atomic clocks come in three types: cesium oscillators, rubidium oscillators, and hydrogen maser oscillators. The most accurate are cesium oscillators, which are used on GPS satellites. BeiDou uses rubidium and hydrogen clocks, which are the lowest priced and smallest and can keep time within less than 1 millisecond in a few months. But they drift slowly with time and must occasionally be reset, and aging effects often limit their long-term stability.[115]

The PRC has used a combination of domestic and foreign atomic clocks for its BeiDou satellites. The PRC's domestic effort appears to have been conducted by four entities: the China Aerospace Science and Industry Corporation (CASIC) 203 Research Institute, CAST's Xi'an Branch, Beijing University, and CAS.[116] According to a 2014 report, the CAST Xi'an Branch had built 28 rubidium clocks for BeiDou 2 satellites launched before 2012, whereas the CASIC 203 Research Institute had supplied 10 rubidium clocks.[117] Since then, the CASIC 203 Research Institute appears to be the primary developer of atomic clocks for BeiDou. In 2018, PRC press announced that BeiDou 3 satellites were equipped with a rubidium atomic clock and a hydrogen atomic clock manufactured by the CASIC 203 Research Institute.[118] It was reported in 2019 that the CASIC 203 Research Institute had started mass producing super-thin rubidium atomic clocks and that it was the only group in China that had developed the technology.[119]

The PRC's atomic clock development has also benefited from foreign technology. The first BeiDou 2 M1 satellite launched in 2007 used only PRC-manufactured clocks but experienced problems with its timing mechanisms.[120] As a result, the plan to use domestic atomic clocks was scrapped, and instead PRC engineers decided to use two domestic clocks and two foreign clocks for each satellite.[121]

Subsequent satellites used a combination of domestic and Swiss atomic clocks from the Swiss company Temex (later sold to SpectraTime and then to the Canadian company Orolia).[122] The PRC reportedly purchased 18 to 20 rubidium clocks from Temex.[123] A 2007 initial public offering document for Orolia stated that the company's main export contract was to the PRC for atomic clocks and that it would complete that contract in 2008; it also noted that it had built a "trusted relationship" with the China National Space Administration.[124] The document noted that Orolia was selected to participate in the first phase of the development of the BeiDou program and was expecting to be chosen for the second phase of the program. It also noted that no U.S. suppliers had been asked to participate in the project and that domestic PRC suppliers were likely unable to develop equipment as advanced as Orolia's products.[125] According to one 2012 assessment, BeiDou 2 clocks did not match the performance of GPS Block IIF clocks (first launched in 2010) but were similar in performance to the clocks of older generations of GPS.[126]

Because of a rise in prices of the foreign clocks and restrictions on their export, however, program engineers were forced to develop clocks domestically, so the last three BeiDou 2 satellites launched before 2013 were equipped with only domestically manufactured atomic clocks.[127] According to one PRC engineer working on BeiDou, the use of domestic atomic clocks "broke" the foreign supplier monopoly of atomic clocks and eventually resulted in the development of a PRC rubidium clock that would lose only 1 second over 3 million years.[128]

CHAPTER 5: BEIDOU-RELATED INDUSTRIAL POLICY

Of China's space programs, perhaps none has more dual-use potential than BeiDou. As a result, BeiDou is a prime example of civil-military integration that harnesses the innovative potential of commercial high-technology firms and the organizational strengths of the defense industry to develop technologies with both military and civilian applications.[129] China's policy is to develop a globally competitive indigenous satellite navigation industry through a three-part strategy of prioritizing development of BeiDou in its industrial plans, mandating the use of BeiDou, and forming a satellite navigation R&D base.

CHINA'S SATELLITE NAVIGATION INDUSTRY

Leveraging BeiDou's dual-use nature, the PRC satellite navigation industry is composed of more than 14,000 companies divided between three segments: a space segment, a ground segment, and a user segment (see Table 4 and Table 5). The space and ground segments, which involve the manufacture of satellites and ground control equipment, are dominated by state-owned conglomerates. The user segment, which involves the manufacture of commercial products, is composed of a mix of state-owned enterprises and private companies. The user segment can be further divided into upstream, midstream, and downstream blocks.

- **Upstream**: companies making chips, antennas, electronic boards, and other hardware or software modules.
- **Midstream**: integrators and terminal manufacturers.
- **Downstream**: companies operating and providing GNSS-based services to the end user.[130]

Table 4. Makeup of PRC satellite industry: space, ground, and upstream user segments

Segment	Industry Chain Links	Products and Services	Companies
Space segment	Satellite design		CAST; CAS Innovation Academy for Microsatellites
	Satellite manufacture		CAST; CAS Innovation Academy for Microsatellites
	Satellite launch		China Academy of Launch Vehicle Technology
Ground segment	Main control station; uplink station; inspection station		China Electronics Technology Group Corporation (CETC) 39th Research Institute (RI); CETC 20th RI; CETC 54th RI
User segment	Upstream	Microchip	CETC 24th RI; Runxin Information Technology Co., Ltd.; Xi'an Huatek Technologies Co., Ltd.; Zhongke Microelectronics; Xi'an Xinchuang Electronic Technology Co., Ltd.
		Functional unit	Unicore Communications, Inc.; Techtotop MICROELECTRONICS Technology Co., Ltd.; Xi'an Huatek Technologies Co., Ltd.
		Printed circuit board	ComNav Technology, Ltd.
		Antenna	Jiali Electronic; Jinchang Electronic; Ayia Electronic Tech Co., Ltd.; Shanghai HighGain Information Technology Co., Ltd.; Harxon Corporation
		Basic products	Beijing BDStar Navigation Co., Ltd.; China Aerospace Science and Technology Corporation (CASC); Long March Launch Vehicle Technology Co., Ltd.; Guizhou Space Appliance Co., Ltd.

Source: "A Publication to Have You Understand China's BeiDou Satellite System Industry and Market Development and Current Situation Analysis Downstream Industrial Chain Growing Rapidly" (一文带你了解中国北斗卫星导航系统产业市场发展现状分析 产业链下游增长迅速), *Forward-The Economist* (前瞻经济学人), https://www.qianzhan.com/analyst/detail/220/200612-b3ccbb9a.html.

Table 5. Makeup of PRC satellite industry: midstream and downstream user segments

Segment	Industry Chain Links	Products and Services	Companies
User segment	Midstream	Terminal products	Shinco; Beijing Intercity Hi Tech Information Technology Co., Ltd.; Space Star Technology Co., Ltd.; Chengdu Corpro Technology Co., Ltd.; Beijing BDStar Navigation Co., Ltd.; Garmin Ltd.; Saige Navigation; UniStrong; CASC; NavInfo Co., Ltd.; Hi-Target Navigation Technology Corporation; Shenzhen Roadrover Technology Co., Ltd.; Jiangsu Leike Defense Technology Co., Ltd.; Hwa Create; Guangzhou Haige Communications Group Incorporated Company; BeiJing StarNeto Technology Co., Ltd.; SuperMap; Navior Co., Ltd.; Hanghai Huace Navigation; Henzhen Coship Electronics Co., Ltd.; Long March Launch Vehicle Technology Co., Ltd.
	Downstream	Operation and services	Beijing eGOVA Co., Ltd.; CASC; NavInfo Co., Ltd.; UniStrong; Hi-Target Navigation Technology Corporation; Guangzhou Haige Communications Group Incorporated Company; Chengdu Corpro Technology Co., Ltd.; Anhui Sun-Create Electronics Co., Ltd.; BeiJing StarNeto Technology Co., Ltd.; Duolun Technology; Hanghai Huace Navigation

Source: "A Publication to Have You Understand China's BeiDou Satellite System Industry and Market Development and Current Situation Analysis Downstream Industrial Chain Growing Rapidly."

INDUSTRIAL POLICY

The BeiDou program has been governed by several regulatory and policy documents, including a series of 5-year, 10-year, and 15-year plans that provide the main objectives and tasks for the period governed.[131] Intended to govern macro-level economic and S&T policy, these documents include BeiDou as an important element of the PRC's modernization drive.

National Medium and Long-Term Development Plan for Satellite Navigation

The most important document dedicated to governing the development of BeiDou appears to be the *National Medium and Long-Term Development Plan for Satellite Navigation* (MLP).[132]

Released in 2013, the MLP governed the period of the 12th and 13th Five-Year Plans (FYPs) (2011–2020).

The MLP prioritized the role of the commercial industry in the development of satellite navigation technologies and included using both domestic and international resources and markets to promote BeiDou's development. The MLP envisioned a satellite navigation market that increased to 400 billion yuan by 2020, with BeiDou capturing a 60 percent share of the overall satellite navigation market and an 80 percent market share in important applications, likely referring to the electrical power generation, finance, and communication sectors.[133]

Special Plan for the Application of the BeiDou Satellite Navigation System in the Transportation Industry

The *Special Plan for the Application of the BeiDou Satellite Navigation System in the Transportation Industry* was released in November 2017 by the Ministry of Transportation and the Central Military Commission (CMC) Equipment Development Department. The special plan encourages the development and promotion of BeiDou in the transportation sector domestically and internationally through 2025 while adhering to China's national security and military-civil fusion strategies. The special plan called for 80 percent of the road vehicles and ships and 100 percent of the aircraft and trains operating in China to use BeiDou by 2020.[134]

The special plan called for BeiDou to be further integrated into China's transportation infrastructure through several projects by 2025. It also called for promoting BeiDou's participation in international organizations such as the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO) and promoting BeiDou in international standards.[135]

2006–2020 Medium and Long-Term Plan for Science and Technology Development

The *2006–2020 Medium and Long-Term Plan for Science and Technology Development* (中长科学和技术发展规划纲要) was the first and most prominent national plan governing the development of BeiDou. One of the most prominent features of the plan was "megaprojects" that prioritized development in 16 technological areas, one of which was satellite navigation.[136] This plan required the development of a GNSS by 2020.[137]

Innovation Driven Development Strategy

The PRC's S&T enterprise is governed by the Innovation Driven Development Strategy (IDDS), introduced by Xi Jinping in 2012. The IDDS stresses domestic innovation, building a market-oriented system for technological innovation, and strengthening basic research.[138] The IDDS called for China to become an innovative country by 2020, to "move to the forefront of innovative countries" by 2030 (subsequently revised to 2035), and to become a "strong global innovation power by 2050."[139] The IDDS called for "industrial technology innovation system

innovation" in 10 areas, including advanced "space application technologies," by promoting, in part, satellite navigation and positioning services.[140]

14th Five-Year Plan

The PRC is also governed by a series of documents that lay out economic and S&T priorities and goals in five-year increments called Five-Year Plans (FYPs). The current 14th FYP governs 2021 to 2025. Formally known as "The Outline of the 14th Five-Year Plan and Vision 2035 for the National Economic and Social Development of the People's Republic of China," the 14th FYP continued the PRC government's emphasis on satellite navigation by designating it as one of six major projects, with a particular emphasis on developing China's satellite navigation industry.[141]

During the 14th FYP, the government will work to make BeiDou more technologically advanced, global, and effective in terms of operations, commercialization, and industrialization.[142] The plan also calls for funding from central and local governments to support commercial companies in the development of BeiDou.[143]

14th Five-Year Plan for Informatization

In December 2021, the PRC State Council released the 14th FYP for Informatization, which governs the development of information technology in China from 2021 to 2025. The FYP for Informatization calls for the PRC to build hubs for an air and space information network based on BeiDou and communication and remote sensing satellites. The plan calls for developing BeiDou into an "intelligent" system, developing a nationwide timing and dispatch system for the nation's rail system, and constructing an international road system based on BeiDou.[144] The plan also calls for major projects for the industrialization of BeiDou and the further commercialization of BeiDou.[145]

Specific industrial policies

The 2013 MLP appears to have initiated several preferential policies that popularized BeiDou and sped up its development. Suggesting the intent to separate strategic sectors of the PRC economy from dependence on GPS, the MLP called for BeiDou to be the exclusive satellite navigation system for China's electrical power generation, finance, and communication sectors.[146] That same year, the PRC government also began piloting regulatory policies requiring state-owned and commercial users to install BeiDou receivers as a way to test the technology on a large scale, encourage widespread adoption, and grow the market for BeiDou applications. Under the threat of license revocation, the Ministry of Transport required 80 percent of coach buses and transport vehicles in nine provinces to install BeiDou navigation receivers (roughly 80,000 in total) and required new heavy and semi-trucks entering the PRC market to be equipped with BeiDou receivers.[147] The move to mandate the adoption of BeiDou was extended to other sectors. The *New*

York Times reported that by 2014, more than 50,000 PRC fishing boats were equipped with the system.[148] In 2021, the China Aerospace Science and Technology Corporation posted a message on a social media account stating that by 2024 all PRC-operated civilian passenger aircraft must have BeiDou receivers installed. The decision was expected to affect around 3,800 aircraft.[149]

PRC policy also sought to explicitly limit the role of foreign companies in BeiDou's development. According to a U.S.-China Economic and Security Review Commission report, PRC companies were "given early access to BeiDou reference designs and specifications, providing an early advantage in developing BeiDou products." China also established certification hurdles "seemingly targeting non-Chinese vendors" and did not allow U.S. chip maker Qualcomm to join China's GNSS standards committee.[150]

The government has also provided financial support for the commercialization of BeiDou. In 2013, for example, China reportedly planned to invest 7 billion yuan (U.S. $1.13 billion) in industries related to BeiDou.[151] In 2023, the Zhuzhou Economic and Technology Development Zone announced the establishment of a fund with an initial investment of 200 million yuan.[152]

R&D infrastructure

The MLP also began the establishment of an R&D organizational system made up of key laboratories, engineering research centers, enterprise research centers, and industrial parks that are intended to make breakthroughs in satellite navigation computer chip technologies and software.[153]

Key laboratories

Key laboratories are among the most elite research organizations in China and can be found at the national, provincial, ministerial, municipal, and institute level (see Table 9).[154] The first national-level satellite navigation key laboratory was the State Key Laboratory for Satellite Navigation and Equipment Technology established in 2016 under the China Electronic Technology Corporation's 54th Research Institute.[155] The laboratory focuses on intelligent navigation and location services, system measurement and time synchronization, navigation enhancement, signal monitoring, and performance evaluation.[156] Since then, other key laboratories have been established at the provincial and national central city levels.

Table 6. Selected satellite navigation key laboratories

Name	Chinese Name
State Key Laboratory for Satellite Navigation and Equipment Technology	卫星导航系统与装备技术国家重点实验
Jiangsu Military-Civil Fusion BeiDou Navigation Key Laboratory	江西省军民融合北斗通航重点实验室
Anhui Province Key Laboratory for BeiDou Satellite Navigation Technology	北斗卫星导航技术安徽省重点实验室

Name	Chinese Name
Shanghai Key Laboratory of Navigation and Location Based Services	上海市北斗导航与位置服务部市共建重点实验室
Xiamen BeiDou Application Technology Key Laboratory	厦门市北斗应用技术重点实验室
Guangxi Key Laboratory for Precision Navigation Technologies and Application	广西精密导航技术与应用重点实验室
Chinese Academy of Sciences Key Laboratory of Precision Navigation and Timing Technology National Time Service Center	中国科学院精密导航定位与定时技术重点实验室
Tianjin Railway Navigation and Positioning and Geospatial Big Data Technology Key Laboratory	天津市轨道交通导航定位及时空大数据技术重点实验

Note: Additional information is available in the Reference list. See endnote 155.

Engineering research centers

Engineering research centers are responsible for practical research and demonstration platforms (see Table 9).[157] Seven engineering research centers working on BeiDou-related projects have been identified by this project.

Table 7. Selected satellite navigation engineering research centers

Name	Chinese Name
National University of Defense Technology Navigation and Timing Technology Engineering Research Center	国防科技大学导航与时空技术工程研究中心
BeiDou Railway Industry Engineering Research Center	北斗铁路行业工程研究中心
BeiDou Applications Engineering Technology Research Center	北斗应用工程技术研究中心
BeiDou Navigation Equipment and Timing Information Technology Railroad Industry Engineering Research Center	北斗导航装备与时空信息技术铁路行业工程研究中心
Guangdong BeiDou Application and Disaster Prevention and Mitigation Engineering Technology Research Center	广东省北斗应用与防灾减灾工程技术研究中心
Xuzhou Beidou Satellite Navigation Engineering Research Center	徐州市北斗卫星导航工程研究中心
Henan BeiDou Navigation Chip Integration and Application Engineering Technology Research Center	河南省北斗导航芯片集成与应用工程技术研究中心

Sources: See endnote 158.

Among these, the National University of Defense Technology's Navigation and Timing Technology Engineering Research Center appears to be an important defense-related center. The center was established in 1994—the year the BeiDou program was officially started—and played an early role in achieving technological breakthroughs. The center started with just 3 researchers and now has nearly 300 employees. Researchers from the center developed an electromagnetic "shield" to prevent electronic interference with the BeiDou signal, which has been regarded as a major achievement for BeiDou 2 and improved the core signal of BeiDou 3. Researchers from the center have also been involved in increasing the amount of information that can be sent by BeiDou's SMS function from 120 characters to 1,000 characters.[158]

Enterprise technology centers

Enterprise technology centers are commercial R&D centers especially designated by the government to conduct R&D in important commercially competitive sectors (see Table 8). Of these, BDStar Navigation appears to be particularly prominent. The company was founded in 1994 as part of the defense industry under the name the Beijing Jinghuida New Technology Co., Ltd. and changed its name to BDStar Navigation in 2000.[159] The company states that it has revenue of 7 billion yuan and 4,000 employees that manufacture products related to satellite navigation, self-driving cars, and microwave ceramic devices. The company appears to have played a leading role in BeiDou chip development and manufactures a 22-nanometer chip for BeiDou receivers that the company states is the most advanced chip of its kind.[160]

The company's main business line is car navigation systems, but it also appears to have a significant military business. It supplies the PLA with navigation terminals and command systems capable of accessing the encrypted military code. In 2013, the company was also reportedly planning to spend "tens of millions of dollars" to set up a BeiDou ground station network in Pakistan.[161]

Table 8. Enterprise technology centers

Name	Chinese Name
BDStar Navigation	北斗星通
TKD Science and Technology Co., Ltd.	泰晶科技
Shanghai Huace Navigation Technology Ltd.	上海华测导航技术股份有限公司
Wuhan Yixun BeiDou Geospatial Technology Co. Ltd.	武汉依迅北斗时空技术股份有限公司
Shanghai Aerospace Electronics Co.	上海航天电子有限公司
Henan Beidou Technology Co.	河南省北斗科技有限公司技术中心
Changsha Beidou Industry Security Technology Research Institute Co.	长沙北斗产业安全技术研究院股份有限公司
Technology Center of Sichuan Jiuzhou Beidou Navigation and Location Service Co.	四川九洲北斗导航与位置服务有限公司技术中心
Chengdu Spaceon Elect Co.	成都天奥电子股份有限公司

Sources: "Qualification and Honor" (资质荣誉), BDStar Navigation (北斗星通), https://www.bdstar.com/mobile/about.aspx?type=6; "TKD Science and Technology Was Selected as 'National Enterprise Technology Center'"(泰晶科技入选"国家企业技术中心"), Suizhou Municipal People's Government (随州市人民政府), Feb. 23, 2023, http://www.suizhou.gov.cn/zwgk/xxgk/kjglhxmjf/202302/t20230223_1082737.shtml; "Enterprise Introduction" (企业介绍), Huace Navigation (华测导航), https://www.huace.cn/about/intro; "Wuhan Yixun BeiDou Geospatial Technology Co. Ltd." (武汉依迅北斗时空技术股份有限公司), Liepin (猎聘), https://www.liepin.com/company/12370639/; "Shanghai Aerospace Electronics Co. Awarded as National Enterprise Technology Center" (上海航天公司获评国家级企业技术中心), Stock 10JQKA (同花顺财经), July 22, 2022, http://stock.10jqka.com.cn/20220722/c640645296.shtml; "Chengdu Spaceon Elect Co." (成都天奥电子股份有限公司), China Satellite Navigation Conference (中国卫星导航年会), https://www.beidou.org/exhibitordetail_205.html; "Congratulations: Our Company Was Awarded the City Recognized Enterprise Technology Center" (喜报：热烈祝贺我公司荣获市认定企业技术中心), Beidou Technology ICT Integrated Solutions (北斗科技 ICT 综合解决方案), https://beidoukeji168.com/news/191; "Notice on the Announcement of the List of Provincial-Level

Enterprise Technology Centers in Hunan Province in 2022 (the 27th Batch)" (关于公布 2022 年度湖南省省级企业技术中心名单（第 27 批）的通知), Industry and Information Technology Department of Hunan Province (湖南省工业和信息化厅), Nov. 2, 2022, http://gxt.hunan.gov.cn/xxgk_71033/tzgg/202211/t20221102_29112968.html; "986! Full List of Enterprise Technology Centers in Sichuan Province Released" (986 家！四川省企业技术中心全名单发布), Scol.com.cn (四川在线), Jan. 4, 2019, https://sichuan.scol.com.cn/ggxw/201901/56793783.html.

Industrial parks

The 2013 MLP also promoted the formation of industrial parks for the development of satellite navigation products through the clustering of military, defense industry, and academic organizations. The BeiDou West Hongqiao Base was China's first BeiDou industrial park. It was established in 2013 by the former PLA General Armament Department and the Shanghai Municipal Government and by 2021 had 176 companies involved in commercializing BeiDou.[162]

Since 2013, China's network of BeiDou industrial parks has expanded (see Figure 4).[163] By 2017, more than 40 industrial parks had emerged in 5 major regions: Beijing-Tianjin-Hebei, the Pearl River Delta, the Yangtze River Delta, Hubei-Henan-Hunan, and Sichuan-Shaanxi-Chongqing, with the majority located in the cities of Beijing, Shanghai, Nanjing, Wuhan, Changsha, Shenzhen, Guangzhou, Chengdu, and Xi'an.[164] These industrial parks have attracted the majority of the leading satellite navigation companies, including 42 of the 58 companies listed on PRC stock exchanges. The companies in these 5 regions also accounted for 80 percent of the total output value of China's satellite navigation industry in 2017. Because of the high cost of entry into the market, most of the companies located in these industrial parks were the result of joint ventures between provincial and local governments and universities and governments and commercial companies.[165]

Figure 4. BeiDou industrial parks

西部川陕渝

West Region Chengdu-Chongqing-Xi'an (West Triangle Economic Zone)

四川省北斗衛星導航產業聯盟
Sichuan Beidou Satellite Navigation Industry Alliance

重庆两江新区北斗导航产业园
Beidou Navigation Industrial Park in Chongqing Liangjiang New Area

成都西部地理信息科技产业园
Chengdu Western Geo-Information Technology Industrial Park

甘肃北斗卫星导航产业园
Gansu Beidou Satellite Navigation Industrial Park

西安北斗经济产业园
Xi'an Beidou Economic Industrial Park

西安北斗应急产业园
Xi'an Beidou Contingency Industrial Park

航天恒星卫星应用产业园
Aerospace Stellar Satellite Application Industrial Park

成都市北斗产业园
Chengdu Beidou Industrial Park

西華中鄂豫湘

Central China Hubei-Henan-Hunan

国家地球空间信息武汉产业化基地
National Geospatial Information Wuhan Industrialization Base

国家级北斗科技城黄石产业园
National-level Beidou Science and Technology City Huangshi Industrial Park

秭归北斗卫星导航产业园
Zigui Beidou Satellite Navigation Industrial Park

赣州北斗产业园
Ganzhou Beidou Industrial Park

国际级畚斗科技城黄石产业园
International Dustpan Science and Technology City Huangshi Industrial Park

长沙北斗导航产业基地
Changsha Beidou Navigation Industry Base

湖南省军民结合卫星应用产业园
Hunan Provincial Military-Civilian Combined Satellite Application Industrial Park

株洲北斗产业园
Zhuzhou BeiDou Industrial Park

京津冀

Jing-Jin-Ji (Metropolitan Region)

北京合众思壮卫星导航产业园
Beijing Unistrong Satellite Navigation Industrial Park

中关村导航产业示范基地
Zhongguancun Navigation Industry Demonstration Base

北京北斗卫星导航民用开发技术创新孵化园
Beijing Beidou Satellite Navigation Civil Development Technology Innovation Incubation Park

北京亦庄卫星导航产业园
Beijing Yizhuang Satellite Navigation Industrial Park

国家北斗产业园区
National Beidou Industrial Park

天津北斗战略新兴产业园
Tianjin Beidou Strategic Emerging Industry Park

北卫星导航产业园
Hebei Satellite Navigation Industry Park

北京市北斗产业创新基地
Beijing Beidou Industry Innovation Base

长三角

Yangtze River Delta

上海浦江卫星导航应用浦江产业基地
Shanghai Pujiang Satellite Navigation Application Pujiang Industry Base

上海北斗卫星导航应用产业基地
Shanghai Beidou Satellite Navigation Application Industry Base

国家北斗导航应用上海产业基地
National Shanghai Industrial Base for Beidou Navigation Applications

司南北斗产业园
Sinan Beidou Industrial Park

上海西虹桥北斗产业基地
Shanghai West Hongqiao Beidou Industry Base

上海北斗启东产业园
Shanghai Beidou Qidong Industrial Park

中国北斗卫星导航(南京)产业基地
China Beidou Satellite Navigation (Nanjing) Industry Base

昆山北斗产业园
Kunshan Beidou Industrial Park

珠三角

Pearl River Delta

广东省北斗卫星导航产业(广州)基地
Guangdong Beidou Satellite Navigation Industry (Guangzhou) Base

无线电集团海格通信北斗产业园
Radio Group Haige Communication Beidou Industrial Park

中国航天中山北斗物联网产业基地
China Aerospace Zhongshan Beidou Internet of Things (IOT) Industry Base

中山北斗卫星导航产业园
Zhongshan Beidou Satellite Navigation Industrial Park

广州中马钦州产业园
Guangzhou China-Malaysia Qinzhou Industrial Park

赛格导航龙岗国家级卫星导航产业基地
SEG Navigation Longgang National Satellite Navigation Industry Base

汕头卫星应用产业园
Shantou Satellite Application Industrial Park

Sources: See endnote 164.

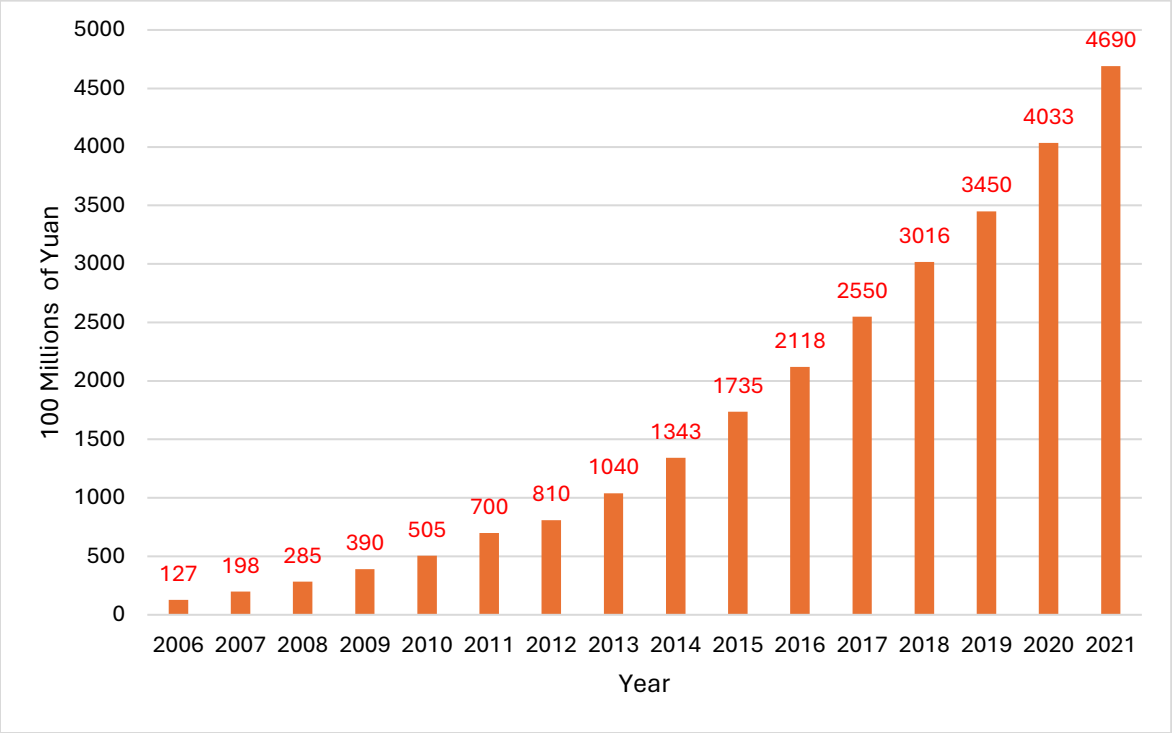
STATED ACCOMPLISHMENTS

The various measures to promote BeiDou have reportedly been effective. According to the GNSS and Location-Based Service Association of China, the total output value for China's satellite navigation industry reached a total of 403.3 billion yuan ($62.7 billion) in 2020, exceeding the PRC government's goal of 400 billion yuan, and reached nearly 470 billion yuan in 2021 (see Figure 5). BeiDou-based services in health care, epidemic prevention, remote monitoring, and online services sectors alone accounted for nearly half of the output—200 billion yuan.[166]

BeiDou's market share has increased exponentially over the last 10 years. In 2013, for example, 95 percent of the cell phones, watches, and navigation devices sold in China relied on GPS. In 2011, only 50 to 60 companies provided BeiDou services or conducted R&D on applications for BeiDou. At the same time, more than 6,800 companies were involved in businesses related to GPS.[167] By 2021, however, more than 14,000 PRC companies were involved in the satellite navigation industry, employing more than 500,000 people.[168]

The PRC press and government now report that BeiDou is widely used across a range of industries and applications, including transportation, public security, agriculture, fishing, forestry, hydrological monitoring, weather forecasting, communications, electric power, and disaster prevention and mitigation.[169] More than 1 billion BeiDou terminals are in use in China and are installed on more than 7.8 million road transportation vehicles, more than 40,000 postal express vehicles, and more than 47,000 ships.[170] Approximately 8,000 terminals are in use on China's railway network, and more than 100,000 farm machines have been installed with BeiDou terminals.[171] In 2021, 324 million smartphones supported by BeiDou were purchased in China, accounting for 94.5 percent of the country's total.[172] BeiDou is used more than 100 billion times on average every day for map navigation on mobile phones.[173] Looking toward the future, the PRC government has identified 16 cities, including Beijing, Shanghai, Guangzhou, Wuhan, Chongqing, Shenzhen, Xiamen, and Nanjing, as pilot cities for the development of a "BeiDou + Intelligent Networked Vehicles" project to develop smart city infrastructure and self-driving vehicles.[174]

Figure 5. BeiDou market size



Source: GNSS and LBS Association of China, "BeiDou Radiance Increases, Market Size Continuously Increases (北斗辐射带动力增强，市场规模不断提升), *Satellite Application* (卫星应用) 6 (2022): 67–72.

One of the most important components for popularizing BeiDou has been the development of chips that enable mobile devices to receive signals from BeiDou. Development of a chip for BeiDou has been a top priority, and in 2021, a 22-nanometer chip began to be mass produced. According to PRC industry sources, the chip is the most advanced in the world for use with satellite navigation signals and can receive signals from all GNSS. According to a PRC industry spokesperson, the chip will help facilitate the integration of BeiDou with 5G communications, artificial intelligence (AI), and the Internet of Things.[175] According to Ran Chengqi, director of the CSNO, chip development completes the BeiDou industrial chain of chips, modules, boards, terminals, and operation services.[176]

The main impediment to using domestically manufactured chips and boards has been their cost. Domestically manufactured chips for BeiDou in 2013 cost around 199 yuan (approximately U.S. $33), several times higher than the cost of GPS chips.[177] In that same year, U.S. chip maker Qualcomm and South Korean cell phone manufacturer Samsung announced that they were collaborating to launch a China market version of the Samsung Galaxy Note 3 as the first smartphone to use the BeiDou signal. The chip, developed by Qualcomm, and the phone, developed by Samsung, were designed to access signals from GPS, GLONASS, and BeiDou.[178]

By 2020, the cost for BeiDou chips had been reduced to around 6 yuan, and high-precision boards cost less than 3,000 yuan. By 2022, smartphone manufacturers such as Xiaomi, Huawei, Nubia, OPPO, VIVO, Coolpad, and Apple were also marketing cell phones supported by BeiDou.[179] In the first three quarters of 2021, 72.3 percent of the cell phones sold in China supported BeiDou's positioning function, accounting for 93.5 percent of the total sales volume. BeiDou's ground-based augmentation function has also been introduced into smartphones to achieve positioning accuracies of 1 meter, and lane-level navigation using BeiDou-supported cell phones is being piloted in several cities in China.[180]

A feature available with the BeiDou chip that is not available with other chips is the ability to incorporate BeiDou's SMS function into cell phones. This feature allows users to send text messages when cellular service is unavailable and does not require changing SIM cards or phone numbers when traveling overseas.[181] One day before Apple announced its satellite-based SOS feature for its iPhone, Huawei introduced a similar feature using BeiDou's SMS function, which enables users to send text messages and "their geographic coordinates using a special app and generate a map of their path while the cellular connection is unavailable."[182]

CHAPTER 6: MILITARY APPLICATIONS

The military utility of BeiDou is inherently tied to the way the PLA plans to fight wars. The PLA takes the ability to use information and deny its use to an adversary as the key determiner of battlefield success in what it calls "informatized local wars."[183] Informatized local wars emphasize joint operations and the technology necessary to connect units not only vertically through a chain of command but also horizontally across different combat arms and services fighting in different domains. A primary focus of the PLA is the development of capabilities and doctrine to conduct long-range precision strikes.

A major component of developing the PLA into an informatized force capable of conducting long-range precision strikes has been the creation of a networked command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) system and the adoption of a concept known as systems destruction warfare.[184] Similar to the U.S. concept of network-centric warfare, systems destruction warfare "accelerate[s] operational response times to enhance firepower and maneuver, particularly by shortening and streamlining decision making and sensor to shooter times to get inside an opponent's decision cycle."[185] As a result, systems destruction warfare requires a C4ISR system to support long-range precision strikes through an organically integrated sensor-to-shooter network that combines multiple weapon systems, sensors, communication systems, navigation systems, and battlefield management systems to provide effective and secure information support to an operational command center.[186]

Systems destruction warfare was followed by a new "core operational concept" called Multi-Domain Precision Warfare (MDPW; 多领域精确战) that further emphasizes precision strike. According to the U.S. Defense Department:

> MDPW is intended to leverage a C4ISR network, which the PLA calls the "network information system-of-systems" that incorporates advances in big data and artificial intelligence, to rapidly identify key vulnerabilities in the U.S. operational system and then combine joint forces across domains to launch precision strikes against those vulnerabilities.[187]

BeiDou appears to play a central role in these concepts by enabling force movements, precision-guided munitions delivery, and communications.[188] In particular, the PLA considers long-range precision strike in all warfare domains as critical to modern war.[189] The Defense Department notes that each PLA service is fielding multiple long-range precision strike weapon systems. For example, PLA Air Force (PLAAF) H-6K and PLAN H-6G and H-6J bombers can carry six precision-guided cruise missiles for use against land and maritime targets.[190] The PLAN will also have the capability in the near term "to conduct long-range precision strikes against land targets from its submarines and surface combatants using land-attack cruise missiles."[191] The PLA Rocket Force's ground-based missile forces are said to "complement the air and sea-based

precision strike capabilities of the PLAAF and PLAN" with a variety of short- and medium-range ballistic missiles and ground-launched cruise missiles.[192] Precision-guided munitions are not solely for missiles—the PLA Army employs multiple rocket launch systems such as the A200 that are reported to be aided by BeiDou.[193]

The PLA's use of BeiDou goes beyond enabling precision strike, however. Although the PLA stresses the role of BeiDou in enabling navigation and precision strike, the PLA just as highly values BeiDou's SMS function for two-way communications and data transfer. PRC writings discuss the use of BeiDou in communications between ground units, ships, and aircraft. PLA researchers discuss BeiDou's PNT functions coupled with its SMS functions as forming the foundation for systems to track location and movement. These applications include using the BeiDou SMS function to provide real-time updates to missiles in flight, developing geographic information systems (GIS), and using "red force tracker" and identification friend or foe (IFF) capabilities.

Ultimately, it appears that BeiDou's PNT and communication capabilities will form the basis for turning the PLA into an "intellingentized force" capable of employing AI and autonomous systems. BeiDou's precision positioning and navigation capabilities will provide uncrewed systems with the information to autonomously navigate and close with targets. Its communications function will facilitate situational awareness among autonomous weapons platforms and with command centers not only for human commanders to provide updated instructions but also for autonomous weapons systems to independently coordinate actions among themselves.

THE EVOLUTION OF THE PLA'S USE OF BEIDOU

2002: initial reports of BeiDou being used by the PLA

Although the PLA may now be planning to use BeiDou to guide future robotic missions, in BeiDou's early years, the PLA continued to rely on GPS's superior accuracy. Reporting on the PLA's use of BeiDou appears to have started in 2002—two years after BeiDou 1 became operational. In 2002, the Jinan Military Region incorporated BeiDou into a command system that had previously used GPS.[194] In 2003, BeiDou terminals were provided to an unidentified group army in what appears to be an experimental stage of incorporating BeiDou into PLA operations.[195]

Despite BeiDou 1's benefits, the military recognized that the system had technical limitations that constrained its military applications. For instance, the system's slow speed limited its operational value to the armed forces. Moreover, its active communication system was susceptible to hacking and jamming, which according to one assessment rendered it "not appropriate" for military applications.[196]

2008: first major operational use during earthquake relief efforts

The first major operational use of BeiDou was the rescue and relief effort conducted in response to the 2008 Wenchuan earthquake in Sichuan Province. PRC press called BeiDou one of three critical technologies used in the response, in addition to large cargo aircraft and helicopters. PRC press reporting noted that BeiDou provided positioning and navigation capabilities to PLA and People's Armed Police troops, but that BeiDou's SMS function was also important. The China Satellite Navigation Applications and Management Center (中国卫星导航应用管理中心) supplied 1,000 BeiDou terminals that were used to send more than 740,000 messages at a time when landline service to the disaster area was cut off.[197]

2009: deployed throughout the force and used during exercises

By 2009, it appears that BeiDou was deployed more widely throughout the force. A 2009 article stated that most "first level" units of an unidentified airborne corps had been equipped with BeiDou terminals.[198] In addition, it was reported that all units in Yunnan Province patrolling China's borders with Myanmar, Laos, and Vietnam were equipped with a BeiDou terminal. The terminals provided positioning and navigation information, and patrol units were able to deliver situation reports to their command and receive commands using BeiDou's SMS. The two-way function of BeiDou also allowed the command to track the patrol's movements.[199]

BeiDou also began to be discussed as a prominent feature of PLA exercises in 2009.[200] BeiDou provided secure communications as well as positioning and navigation information during "Stride-2009," a large-scale exercise involving divisions from four military regions.[201] Units from the Chengdu Military Region also used BeiDou to call in airstrikes during the "Northwest Mission-2009" exercise.[202] During this exercise, data from both GPS and BeiDou were used to create an IFF system displayed on command post monitors.[203]

2010: further integration into the force

In 2010, BeiDou was further integrated into the PLA when the CMC ordered BeiDou's timing service to become the timing standard for the entire PLA. Additional evidence indicates that the PLA continued to integrate BeiDou into the force and experiment with its utilization. A 2010 article, for example, stated that a logistics support unit from the Nanjing Military Region was training on BeiDou, the integrated command platform, and logistics command vehicles to improve joint logistics.[204]

According to a 2010 interview with the commander of the Xinjiang Military Region, the two most important tools the military region used in its counterterror operations were BeiDou and helicopters. During border patrols, military units used BeiDou for positioning, navigation, and communication, which allowed commanders to track the patrols' movement. The commander explained, "We want to stress maintaining independence. When GPS encounters a problem, our

BeiDou will not be jammed." Nevertheless, because the military region was using imported equipment at that time, they still relied on GPS for some functions.[205]

2012: employed at the small unit level

The year 2012 marked the formal operation of the BeiDou 2 system, and several 2012 articles indicated the expansion of BeiDou down to the small unit level.

- Each platoon leader of an unidentified combined arms battalion was equipped with a BeiDou receiver.[206]
- Each echelon command vehicle of an unidentified unit was equipped with a BeiDou terminal.[207]
- Every tank in an unidentified mechanized brigade was equipped with BeiDou.[208]
- The "Dynamic Monitoring System for Military Vehicles" was established as an all-Army vehicle test point. The system was operated at four levels: the General Logistics Department, military region, unit, and small unit depot levels.[209]

2013: incorporated into naval command systems

In 2013, BeiDou was described as "essential equipment" during the 2013 "Mission Action" exercises.[210] By this time, the PLAN had also incorporated BeiDou into its ship command systems, which allowed each ship to know the position of other ships in formation. PLAN ships were also using BeiDou's SMS function, which was described as faster and more secure than other types of satellite communications used by the PLAN.[211] In 2016, the *PLA Daily* reported that PLAN ships participating in the Gulf of Aden counterpiracy missions were using BeiDou for command and control.[212] In 2019, it was reported that most Coast Guard ships had been equipped with BeiDou.[213]

2014: PLA issues regulations on use

By 2014, it appears that the use of BeiDou had become widespread enough to require regulations. In May 2014, the GSD issued the *Chinese People's Liberation Army Regulations on the Management of Satellite Navigation Applications*. The regulations were intended to promote the efficiency of the use of satellite navigation within the PLA through standardization and regularization.[214]

At this time, BeiDou terminals were reportedly deployed down to the brigade or regiment level.[215] For example, Beijing Military Region Joint Logistics Department trucks participating in the China-Russia combined exercise Peace Mission-2014 were equipped with BeiDou, which allowed the Joint Logistics Department to monitor the speed of the vehicles to ensure safe driving.[216] Soldiers from the 38th Group Army used a BeiDou-enabled device to report casualties during the Medical Mission-2014 exercise. A "wounded" soldier activated a personal device that alerted medical personnel of the soldier's name and location.[217] Nevertheless, one 2014 article

stated that because of a lack of BeiDou terminals, an unidentified regiment had to coordinate the use of 100 BeiDou terminals for training to accomplish as much individual training as possible.[218] At this time, PLA media also reported that GP155A and GP155B artillery shells displayed at the Zhuhai Airshow were equipped to be guided by BeiDou and GPS.[219]

2016: integrated into combat vehicles

Other evidence also indicates that BeiDou was more widely used. According to a 2016 article, all armored fighting vehicles belonging to the 38th Group Army had been equipped with BeiDou terminals and electronic maps that were networked to enable command and control and precision strike.[220] A 2021 article noted that infantry fighting vehicles from the 72nd Group Army were equipped with BeiDou terminals and that these vehicles were the first infantry fighting vehicles in the PLA to be equipped with an IFF system.[221] In 2017, reconnaissance units from the 71st Group Army were reported to have used BeiDou to call in fire support, and in 2018, training was reported to include operating in a simulated BeiDou-denied environment.[222]

2020 to present: surveying and mapping

Since BeiDou 3 became operational in 2020, the PLA has been surveying and mapping China. Articles appearing in the *PLA Daily* indicate that Strategic Support Force units have been surveying and mapping remote areas of China. The intent appears to be to develop a detailed map of every part of China to assist operational units with meeting their navigation and positioning requirements. A 2020 article, for example, profiles a Strategic Support Force officer who traveled to an island, the desert, and a remote mountainous area to conduct surveying and mapping.[223]

THE PLA'S BEIDOU-RELATED RESEARCH

Whereas media reports provide glimpses into how the PLA has used BeiDou, research articles may provide indications of how the PLA is using BeiDou or plans to expand its use. Research articles indicate interest in further integrating BeiDou as a fundamental component of PLA systems architecture. These articles fall into two categories: (1) the use of BeiDou to develop GIS and (2) the use of BeiDou in facilitating commands to weapons platforms.

Geographic information systems

The most prominent application discussed in PLA research articles is the use of BeiDou to create GIS. *National Geographic* defines GIS as

> a computer system for capturing, storing, checking, and displaying data related to positions on Earth's surface. GIS can show many different kinds of data on one map, such as streets, buildings, and vegetation. This enables people to more easily see, analyze, and understand patterns and relationships.[224]

GIS can help in the tracking of vehicles, supplies, and spare parts to improve the efficiency of logistics and, in the case of China, national defense mobilization. Within the context of

warfighting, BeiDou-enabled GIS can play a role in the creation of "red force trackers" and IFF. Various applications discussed include the following:

- ***Logistics system.*** In a 2013 article, two researchers from the PLA and People's Armed Police proposed a logistics system GIS based on the Internet of Things and BeiDou.[225]
- ***Naval equipment support.*** A 2014 article by PLAN researchers discussed the development of a naval equipment support command automation system that uses a BeiDou-based GIS to track the location of fuel, ammunition, and parts.[226]
- ***Tracking national defense mobilization.*** A 2017 article promoted the use of BeiDou for national defense mobilization. According to the article, national defense mobilization organizations were using BeiDou for navigation, vehicle tracking, and communication.[227]
- ***Civil air defense command.*** A 2016 article by researchers in the PRC electronics industry discussed the use of BeiDou in civil air defense command systems. The article focused on provincial-level civil air defense and stated that province-wide location-based monitoring functions for subordinate command posts, vehicles, and personnel had not yet been established. The article proposed the use of BeiDou to provide location data and communications between command posts, mobile command posts, communication vehicles, and information collection vehicles at the provincial, city, and county levels. It stated that BeiDou's communication function can be used to facilitate communications with a time lag of seconds. It also noted that the use of GPS for PNT is considered insecure.[228]
- ***Air Force logistics management.*** In a 2017 article, researchers from the PLA Air Force Logistics College proposed an equipment support command system in which BeiDou provided real-time data on the location of weapons and equipment, spare parts, fuel, personnel, and transport vehicles. The system also used BeiDou's SMS to facilitate communication and data sharing between equipment support command posts, units, and storage areas.[229]
- ***Strategic Support Force vehicle scheduling.*** A 2018 master's thesis by a student at the PLA Strategic Support Force Information Engineering University examined the development of a GIS facilitated by BeiDou for vehicle scheduling.[230]

Weapon systems command and control

A second set of articles discusses the use of BeiDou's SMS function and PNT capabilities in the command and control of weapon systems. Perhaps the most interesting example is the use of BeiDou to provide inflight updates to cruise missiles, a capability already used by the U.S. Tomahawk cruise missile.[231] Such a capability would allow human commanders to provide inflight course corrections for more responsive targeting and enable missiles to autonomously engage targets. Other applications discussed include the following:

- ***Aircraft command and control.*** A 2015 article by researchers from the PLAAF noted that BeiDou can facilitate positioning and navigation but focused on the use of BeiDou's SMS to facilitate command and control between ground command centers, airborne command aircraft, and other aircraft through the transmission of text messages and data such as aircraft status and navigation.[232]
- ***Integration of BeiDou with radar data.*** A 2016 conference article discussed the integration of BeiDou PNT information with radar data. The article stated that at the time of publication, each PLA service was using a different system, which introduced error into location data, and that a unified system for establishing location was necessary to facilitate joint operations. The article also stated that the PLA was still using timing data from GPS, which posed a risk to operations.[233]
- ***Antisubmarine warfare.*** A 2018 article discussed the use of BeiDou with sonobuoys in antisubmarine warfare. According to the article, determining the precise location of submarines requires knowing the exact location of sonobuoys.[234]
- ***Subsurface navigation.*** In 2019, the Hong Kong–based *South China Morning Post* reported that the China Shipbuilding Industry Corporation's 716 Research Institute was conducting research on the use of BeiDou for subsurface navigation and positioning and for tracking underwater vessels.[235]
- ***Warhead detonation.*** A 2020 article by researchers at the Chongqing University of Posts and Telecommunications discussed the use of BeiDou to determine the burst height of missiles. The researchers found that BeiDou can deliver a stable signal that provides height measurement with an error of 1.25 meters.[236]
- ***Missile inflight updates.*** A 2021 article by researchers at the Naval Engineering University discussed using BeiDou's SMS function to provide real-time updates to inflight antiship missiles in a complex targeting environment.[237] Another 2021 article by PLA researchers discussed the use of BeiDou positioning and navigation services to improve the responsiveness of land-based antiship missiles. The researchers argued that traditional inertial navigation systems lack responsiveness when placed on mobile ship launchers and concluded that using the BeiDou signal for inflight adjustments of missile flight is more responsive than using inertial navigation systems alone.[238] A 2022 article written by a researcher from the PRC defense industry discussed the use of satellite communications to provide real-time updates to missiles. The researcher wrote that the PRC's BeiDou satellites, Tiantong mobile communications satellites, and Tianlian data relay satellites provide similar capabilities. According to the article, communication satellites can enable the autonomy of missiles by facilitating the transfer of targeting data and information on the battlefield situation and facilitating the disposition of other missiles to form a network between ground controllers and missiles as well as among missiles.[239]

CHAPTER 7: PRC EFFORTS TO PROMOTE BEIDOU INTERNATIONALLY

The PRC conducts a wide range of activities related to BeiDou that are intended to enhance its status, influence, and military power globally. PRC efforts to promote BeiDou internationally include cooperative activities, military agreements and arms sales, activities in the polar regions, admission into international standards organizations, and interoperability and compatibility agreements.

International efforts advance PRC interest in several ways:

- Providing access to BeiDou's encrypted military signal can reinforce relations with countries by reducing perceived U.S. leverage and status.
- The use of BeiDou may help facilitate PRC arms sales to countries concerned about dependence on GPS.
- International training and education advance China's efforts to portray itself as a provider of global goods that emphasizes improving the economic development and S&T of developing countries.
- PRC training courses serve a commercial purpose by highlighting the role of PRC companies in providing BeiDou solutions to countries' PNT needs.
- The adoption of PRC products can create dependence on BeiDou, which could provide strategic leverage for the PRC, especially if BeiDou is relied upon in a country's power generation, finance, and communications sectors.
- Participation in global standards organizations promotes BeiDou as a globally accepted alternative to GPS and promotes the image of China as a world leader.
- The use of BeiDou in polar regions helps the PRC to better pursue its interests in those regions.
- Interoperability and compatibility agreements ensure that BeiDou can be used reliably anywhere on the globe.

INTERNATIONAL COOPERATIVE ACTIVITIES

BeiDou international cooperative activities play a role in serving the PRC's foreign policy goal of building "a community of shared future for mankind," which is intended to portray the PRC as a responsible stakeholder in the international system.[240] Through its "community of shared future for mankind" framework, China states that it will improve the lives of people around the world by promoting a "new type of international relations" that acts with benevolence and generosity and bases its relations with other countries on "mutual respect, fairness, justice, and win-win cooperation" and "peace, universal security, and common prosperity."[241]

According to the authors of a 2022 book on BeiDou published by China Astronautics Press, BeiDou is a public good given to the world by China that is intended to serve the world and "contribute China's wisdom and power to the world."[242] Pursuant to this view, the BeiDou program's slogan "Serve the World and Benefit Mankind" represents the PRC's efforts to portray the program as benefiting the international community.[243]

According to the 2022 BeiDou white paper, "By making BDS [BeiDou Navigation Satellite System] available worldwide, China honors its commitment to helping people of all countries share the opportunities and fruits of development."[244] The PRC states that it has promoted "research and consultancy services regarding policies, markets, laws, and finance related to international satellite navigation applications."[245] The 2022 BeiDou white paper also states:

> China engages in active cooperation with other countries and international organizations on technology R&D and the satellite navigation industry. It has set up overseas BeiDou application and industrialization promotion centers and strives to build solid foundations for the satellite navigation industry.[246]

The PRC promotes BeiDou as a key component of the Belt and Road Initiative, especially with regard to building what it calls the "Space Silk Road" (太空丝绸之路), the space component of the PRC's Belt and Road Initiative.[247] According to the white paper, BeiDou

> serve(s) the development of the Silk Road Economic Belt and the [Belt and Road Initiative], and actively pushes forward international cooperation related to the BeiDou system....In line with the Belt and Road Initiative, China will jointly build satellite navigation augmentation systems with relevant nations, provide highly accurate satellite navigation, positioning and timing services, improve [BeiDou's] overseas service performances, and promote international applications of navigation technologies.[248]

In 2013, Thailand became the first country to sign a BeiDou cooperation agreement with China. Since then, the use of BeiDou has expanded to more than 120 countries and regional organizations, including the Asia-Pacific Space Cooperation Organization (APSCO), the Association of Southeast Asian Nations (ASEAN), the African Union, the League of Arab States, and the Community of Latin American and Caribbean States.[249] According to the white paper, the PRC government is "releasing [BeiDou]-based solutions in the fields of smart cities, public security, precision agriculture, digital transport, and disaster prevention and mitigation, which are being piloted in Asia, Africa, and Latin America."[250]

International cooperation comes in a variety of forms, including training and education, the establishment of joint R&D centers, and the building of ground infrastructure, such as CORS. Training and education have been a focus of international cooperation. CSNO established the International Exchange and Training Center in 2012 and has held 18 short-term training courses for more than 800 international students. By 2019, PRC experts had been sent to 13 countries

(Tunisia, Sudan, Morocco, Egypt, Nigeria, Australia, Croatia, Singapore, Pakistan, Indonesia, Thailand, Bangladesh, and Brazil) to conduct training on BeiDou satellite navigation technologies and applications.

China is also hosting postgraduate education for international students.[251] In 2022, it was reported that more than 100 international students from approximately 20 countries had obtained master's and doctoral degrees in China related to BeiDou and that the number of international trainees had increased to more than 1,000 people from more than 50 countries.[252]

2019: used in unmanned border defense system

Indicating BeiDou's further integration and expansion into PLA operations, in 2019, defense conglomerate China North Industries Corporation announced that it would build a border and coastline defense system to provide high-precision monitoring and communication capabilities for border defense personnel and unmanned aerial vehicles (UAVs). The project, called the BeiDou+ Land and Maritime Defense and Control System, involves building continuously operating reference stations (CORS) every 40 to 50 kilometers along the country's land and maritime borders. According to the article, around 2,000 CORS had already been deployed on China's border and interior regions, including in the Xinjiang Uyghur Autonomous Region and Yunnan Province as well as islands and reefs in the South China Sea.[253]

Asia-Pacific Space Cooperation Organization

APSCO is an intergovernmental organization based in Beijing that facilitates space cooperation between the member countries of China, Bangladesh, Iran, Mongolia, Pakistan, Peru, Thailand, and Turkey. Indonesia is a signatory and Mexico has observer status.[254] An area of BeiDou-related cooperation is the APSCO International GNSS Monitoring and Assessment Network, in which APSCO member countries promote the understanding of GNSS monitoring and assessment technology. The project was started in 2017 and involves participating countries monitoring the quality of GNSS signals from BeiDou, GPS, Galileo, and GLONASS.[255]

China and Arab states

BeiDou cooperation between China and the Arab world is based on the "bringing BeiDou to the Arab world project" announced by Xi Jinping in 2016 during a speech at the League of Arab States.[256] That cooperation began in 2016 with the establishment of a framework between CSNO and the Arab Organization for Information and Communication Technology.[257] According to the Tunisian minister of higher education and scientific research, Slim Khalbous, BeiDou cooperation "is the best example for the strategic cooperation between China and Arab states, as satellite navigation integrates many hi-tech areas, including telecommunication and space technologies."[258]

Cooperation between China and the Arab world is said to have resulted in two outcomes:[259]

1. ***The establishment of the China–Arab States BeiDou/GNSS center located in Tunisia on January 20, 2016.***[260] The center officially opened on April 10, 2018, and is the first overseas center for BeiDou.[261] The center is intended to train personnel from Arab states on satellite navigation systems and promote satellite navigation applications.[262] Activities have included training and regional capacity building, exhibitions, testing and assessment, pilot projects, and R&D.[263]
2. ***The establishment of the China–Arab States BeiDou Cooperation Forum.*** To date, three events have been held in 2017, 2018, and 2021 in Shanghai, Tunisia, and virtually, respectively.[264] A focus of BeiDou cooperation appears to be training and education. Training and education events include the following:
    a. Training in Sudan and Tunisia.[265]
    b. Beijing University of Aeronautics and Astronautics, China Agricultural University, and PRC companies conducted training on satellite navigation, geographic information, and satellite navigation applications for 48 trainees from Tunisia, Egypt, Algeria, Iraq, Mauritania, and other countries.[266]
    c. China offered five scholarships to students from Arab countries to conduct postgraduate studies in China on space technologies. In 2019, three students from Egypt and one student from Algeria were selected.[267]

BeiDou cooperation with Saudi Arabia appears to be especially robust. In 2019, the China-Saudi BeiDou/GNSS Center was established.[268] The PRC and Saudi Arabia have also held multiple forums on BeiDou, including the China-Saudi Satellite Navigation Symposium and the China-Saudi Satellite Navigation Cooperation Meeting. In 2022, China and Saudi Arabia signed the China-Saudi Memorandum of Understanding in the Field of Satellite Navigation Cooperation.[269]

Case Study: Pakistan

Pakistan appears to have figured prominently in early PRC plans for expanding BeiDou internationally. Cooperation is reported to have been initiated after a trip by PRC Premier Li Keqiang in 2013. In that same year, China and Pakistan signed an agreement to install five BeiDou ground augmentation stations and one processing center, allowing greater accuracy in the country. The first ground augmentation station was established in Karachi, and coverage was expected to expand to the entire country, although there is no evidence that a nationwide network has ever been completed. The nationwide network was estimated by the international business director of BDStar Navigation, a PRC company, to cost "tens of millions of dollars." PRC press reported that the ability to achieve accuracies as good as 2 centimeters would make for a signal that is "safer and more reliable" than that of GPS. In 2018, the *New York Times* reported that the PRC had provided BeiDou's encrypted military signal to Pakistan.

Sources: Sabena Siddiqui, "Pakistan Benefits from China's Sat-Nav System," China.org.cn, May 23, 2017, http://www.china.org.cn/business/2017-05/23/content_4087pakist3203.htm; "BDStar's Growth Completely Tilts National Defense Navinfo"; Maria Abi-Habib, "China's 'Belt and Road' Plan in Pakistan Takes a Military Turn," *New York Times,* Dec. 19, 2018, https://www.nytimes.com/2018/12/19/world/asia/pakistan-china-belt-road-military.html.

China and Africa

The first China-Africa BeiDou Cooperation Forum was held virtually on November 5, 2021. The forum was organized by CSNO, the China National Space Administration, the Secretariat of the China Follow-up Committee of the Forum on China-Africa Cooperation, the Ministry of Digital Economy and Telecommunications of Senegal, and the Department of Education, Science, Technology and Innovation of the African Union Commission.[270] The forum was attended by more than 600 participants from African countries and the African Union and by nearly 50 representatives of African countries, including 8 government ministers and 8 ambassadors.[271]

The forum resulted in a joint agreement to promote BeiDou through seven cooperative activities:[272]

- Regular information exchange and cooperation mechanisms, including China-Africa BeiDou cooperation forums, application seminars, and related activities.
- Satellite navigation personnel training and education.
- Joint observation and evaluation of BeiDou/GNSS service performance.
- Joint R&D of BeiDou/GNSS technologies.
- Joint establishment and operation of BeiDou/GNSS centers.
- Joint establishment and operation of satellite navigation augmentation infrastructure.
- Support to African industries to develop downstream and upstream satellite navigation technologies.[273]

To what extent the agreement has been implemented is unclear because pandemic restrictions likely limited collaboration.

During the 2021 forum, PRC entities presented 10 examples of how BeiDou was being used in Africa: road transportation, rail transportation, precision agriculture, international search and rescue, land survey, information technology, intelligent mining, public safety, wildlife conservation, and smart cities. Demonstrating China's state support for its satellite navigation industry, each application area was accompanied by the name of the PRC provider(s) and their contact information.[274]

China and the Association of Southeast Asian Nations

China's cooperation with ASEAN countries on satellite navigation goes back to at least 2014 when BeiDou cooperation was discussed at the Second China-ASEAN Technology Transfer and Innovation Cooperation Conference held in the Guangxi Autonomous Region.[275] Later that year, the China-ASEAN Data and Service Center was established in Malaysia to provide products and services in disaster warning, vehicle navigation, agriculture, and maritime search and rescue, among others.[276]

In 2019, the China-ASEAN BeiDou/GNSS (Nanning) Center was established in the Guangxi Zhuang Autonomous Region in southern China to promote the use of BeiDou in ASEAN countries.[277] BeiDou promotion activities are conducted in conjunction with the annual China-ASEAN Expo. In 2020, the center conducted a forum on BeiDou applications and industrial development in conjunction with the 17th China-ASEAN Expo. According to one report, three agreements were signed by companies from China, Thailand, Cambodia, and the Philippines.[278]

Guangxi Autonomous Region has also reportedly built 13 BeiDou navigation application demonstration and industrialization projects directed toward ASEAN. One of these, the China-ASEAN cross-border geological disaster monitoring system, has been demonstrated in Cambodia, Laos, Thailand, Malaysia, and Myanmar.[279]

Case Study: Thailand

Thailand was the first country to become an overseas client for the BeiDou system. In 2013, Thailand and the PRC signed a 2 billion yuan agreement to promote the use of BeiDou for disaster relief, power distribution, and transport. According to a researcher at China's Wuhan University, Thailand was chosen to be the first country to take on BeiDou because it was an ally of the United States. According to the researcher, the PRC government was "eager to show the Thais that BeiDou can do anything GPS does, and in some areas, it can do better." The researcher is also quoted as having claimed that "if Thailand can embrace BeiDou, other countries may follow and the Americans' political, economic, and military power in the region will be reduced."

The agreement between the PRC and Thailand included a satellite ground station and an industrial park for the development and production of BeiDou receivers. The PRC shouldered most of the cost of the 2 billion yuan agreement. This effort appeared to have started in December 2013 when the company Wuhan Optics Valley BeiDou built the first three CORS in eastern Thailand's Chonburi Province. According to the company, it had plans to build 220 stations across Thailand to be used in Thailand's agriculture, urban management, traffic, energy, mine, weather, and watershed management sectors.

Sources: Stephen Chen, "Thailand Is Beidou's First Overseas Client Deal Will See China's Home-Grown Navigation Network Challenging Dominance of US' GPS," *South China Morning Post*, Apr. 4, 2013, https://www.scmp.com/news/china/article/1206567/thailand-beidou-navigation-networks-first-overseas-client; "China's BeiDou System to Expand Cooperation to SE Asia," *China Daily*, Apr. 1, 2017, https://www.chinadaily.com.cn/china/2017-04/01/content_28774844.htm; Li Xiang, Zhou Lihua, and Liu Kun, "BeiDou Reaches New Heights," Hubei People's Government, http://en.hubei.gov.cn/news/newslist/201501/t20150114_610262.shtml.

China and Central Asia

China–Central Asia cooperation on BeiDou appears to be centered on the China–Central Asia BDS Cooperation Forum. The forum was first held in 2019 and is described as China's third international platform to promote the international development of BeiDou, after the China-Russia Satellite Navigation Key Strategic Cooperation Project Committee and the China–Arab States BeiDou Cooperation Forum.[280]

More than 100 delegates attended the 2019 forum from 11 countries (Kazakhstan, Kyrgyz Republic, Tajikistan, Uzbekistan, Turkmenistan, Cambodia, Indonesia, Laos, Thailand, Vietnam, and Pakistan). A second forum was held in 2021 with representatives from China and Turkmenistan, Uzbekistan, and Kazakhstan.[281]

China and Latin American and Caribbean States

On December 3, 2021, the third Ministers' Meeting of the China–Community of Latin American and Caribbean States Forum was held virtually. A joint action plan released after the meeting outlining cooperation in key areas from 2022 to 2024 called for the "active exploration" of cooperation on BeiDou.[282] Little information is available on PRC BeiDou-related activities in Latin America and the Caribbean, however.

Argentina

In February 2022, Argentina joined the Belt and Road Initiative in conjunction with the 50th anniversary of establishment of official PRC-Argentina relations. The two countries also signed a memorandum of understanding on cooperation involving BeiDou.[283] No information has been found on the specifics of this cooperation, however. Attention has focused on the PRC-operated Espacio Lejano satellite ground station in Neuquén, Argentina, but no specific link to BeiDou has been found.[284] The facility provides telemetry, tracking, and control capabilities for China's lunar and Mars exploration programs, but suspicions have arisen over its possible counterspace role, especially because the PRC organization running the facility—China Satellite Launch and Tracking Control General—is reported to be subordinate to the PLA's Strategic Support Force.[285] According to then Commander of US Southern Command Admiral Craig Faller, the station's activities could be "in violation of the terms of its agreement with Argentina to only conduct civilian activities."[286]

Peru

As noted previously, as an APSCO member, Peru is participating in the APSCO International GNSS Monitoring and Assessment Network.[287]

China and Russia

China's most extensive international partnership on satellite navigation is with Russia. China and Russia cooperate on satellite navigation for technological, political, and economic reasons. Although official agreements and communiqués do not explicitly mention competition with the United States, a *People's Daily* article referred to satellite navigation cooperation as a way to "break the 'hegemonic' position of the United States in the field of satellite navigation."[288] According to an article from *Sputnik*, China-Russia satellite navigation cooperation would benefit "the member states of BRICS [Brazil, Russia, India, China, and South Africa] group and the Shanghai Cooperation Organization."[289] In 2015, China and Russia planned a project "to create a global navigation system based on China's BeiDou and Russia's GLONASS satellite navigation for the member states of BRICS group and the Shanghai Cooperation Organization."[290]

BeiDou and GLONASS are complementary systems. Because Russia is located higher in the Northern Hemisphere, the GLONASS system is optimized to cover northern latitudes, whereas BeiDou is optimized to cover more southern latitudes. According to the director of Roscosmos, Dmitry Rogozin, "Their complementariness would result in the biggest and most powerful competitor to any navigation system."[291]

Russia-China Project Committee on Major Strategic Cooperation in Satellite Navigation

The Russia-China Project Committee on Major Strategic Cooperation Projects in Satellite Navigation (中华人民共和国政府和俄罗斯联邦政府关于和平使用北斗和格洛纳斯全球卫星

导航系统的合作协定) was the result of a memorandum of understanding on satellite navigation cooperation signed in October 2014 and was formally established in January 2015.[292] The committee held its first meeting in February 2015 and has met on an annual or biannual basis since then. The committee has four working groups that meet on a more frequent basis and focus on the following topics:[293]

- Ensuring compatibility and interoperability between the GLONASS and BeiDou navigation systems
- Augmentation, including mutual allocation of measuring stations within the territories of Russia and China
- Performance monitoring
- The application of satellite navigation technologies[294]
- The joint committee has produced several outcomes, although little information on them is in the public domain. These outcomes include the following:
- *Joint Statement on the System Compatibility of BeiDou and GLONASS*. Signed in May 2015, this joint statement was described by the PRC government as "an important symbol of the international development of the BeiDou system." It was also described as "marking a new stage in China-Russia satellite navigation cooperation" that strengthened cooperation between the BeiDou and GLONASS systems to promote compatibility and interoperability.[295]
- Agreement on Technical Protection Measures for Cooperation Between the Government of the People's Republic of China and the Government of the Russian Federation on the Construction and Use of Launch Vehicles and Ground Facilities and Equipment in the Field of Peaceful Research and Utilization of Outer Space. Signed in December 2015, the agreement was reported to promote cooperation on the application of the BeiDou and GLONASS systems to provide higher quality satellite navigation services to users worldwide.[296]
- Cooperation Agreement Between Russia's Roscosmos State Space Corporation and the China National Space Administration in the Area of Electronic Components for Space Equipment. The PRC State Administration for Science, Technology, and Industry for National Defense announced a deal in 2015 on the "development and production of aerospace components" between China and Russia involving satellite navigation technologies.[297]
- *Fifth Meeting of the China-Russia Committee on Major Strategic Cooperation Projects in Satellite Navigation*. This meeting was held in Beijing on September 28, 2018. The meeting recognized progress in nine cooperative projects. These projects included

construction of augmentation stations, monitoring and evaluation service platforms, and cross-border transportation applications. It also considered the adoption of the BeiDou/GLONASS Precision Agricultural Cooperation Demonstration Project as the 10th cooperative project.[298]

- Cooperation Agreement Between the Government of the People's Republic of China and the Government of the Russian Federation on the Peaceful Use of the BeiDou and GLONASS Global Navigation Satellite Systems. Signed on November 7, 2018, this agreement provided the legal and organizational basis for cooperation in the field of satellite navigation.[299]
- *Sixth Meeting of the China-Russia Committee on Major Strategic Cooperation Projects in Satellite Navigation*. This meeting was held on August 30, 2019, in Kazan, Russia. The committee agreed on the text of the "Cooperation Agreement on China Satellite Navigation System Commission (People's Republic of China) and the Russian National Aerospace Corporation (Russian Federation) Regarding BeiDou and GLONASS Global Satellite Navigation System Synchronization," the completion of the survey certificate at the site of the China-Russia Satellite Navigation Monitoring Station, the consideration and adoption of the feasibility study report for the precision agricultural project, and the release of the "Global Signal Multimode Multi-Frequency RF Chip of the Sino-Russian Satellite Navigation System."[300]

Monitoring station agreement

In November 2018, China and Russia signed an agreement on the "peaceful use" of BeiDou and GLONASS that was described as providing "a legal and organizational guarantee for the large-scale cooperation in the satellite navigation field between the two countries."[301] The cooperation agreement's language has not been made publicly available; however, the agreement is reported to encourage system compatibility and interoperability, construction of monitoring stations, monitoring and evaluation, joint technology development, and intellectual property rights protection.[302] Russian monitoring stations in China were to be in Shanghai, Urumqi, and Changchun. PRC monitoring stations in Russia were to be in Obninsk, Irkutsk, and Petropav.[303]

Road maps and outlines

The seventh Joint Satellite Navigation Committee meeting was held in October 2020, when the "2021-2025 China-Russia Space Navigation Cooperation Road Map" was discussed. The committee also approved a joint research report on satellite-based augmentation system testing and certification technology.[304] No additional information is available on either document, however.

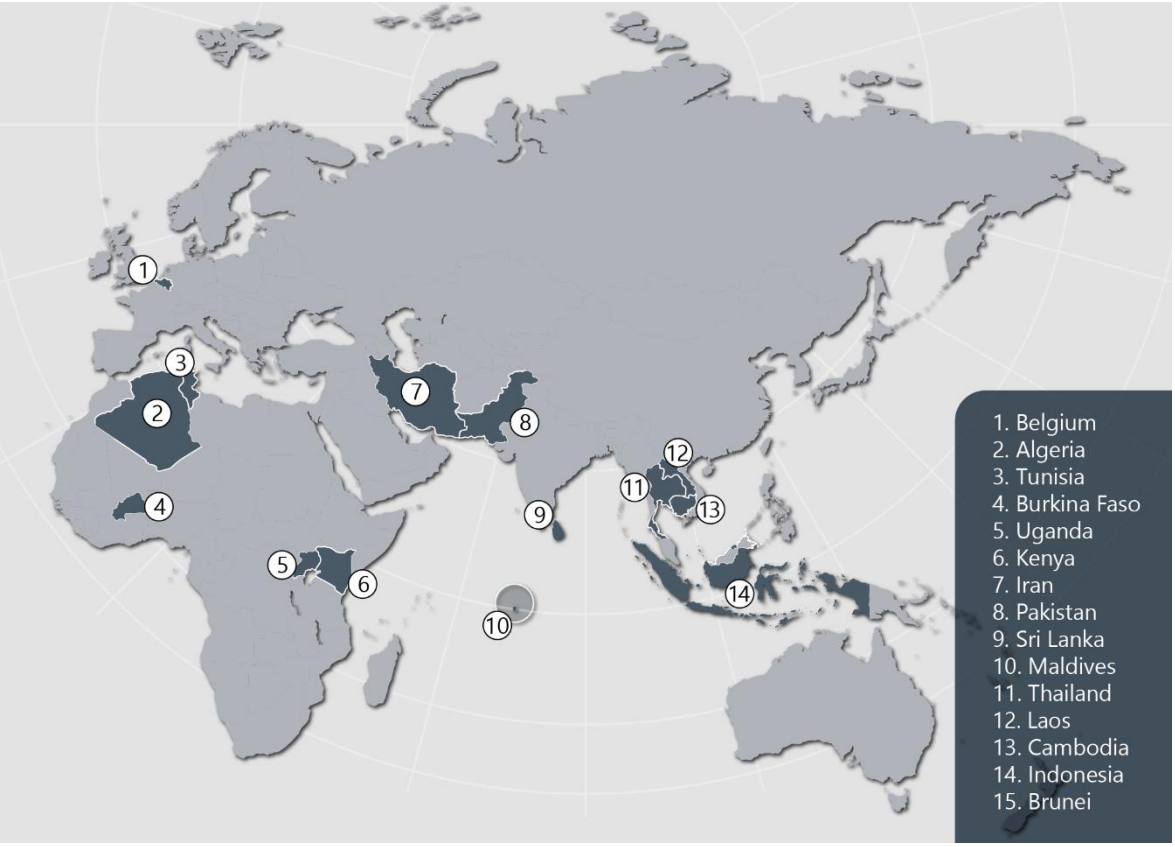
Belt and Road Initiative and satellite navigation

China and Russia are also cooperating on providing satellite navigation to China's Belt and Road Initiative, which seeks to advance a "Space Silk Road."[305] According to the Russian Space Agency's Information and Analysis Center, China and Russia conducted a project on utilizing BeiDou and GLONASS within Russia.[306] Phase one of the project, testing the two systems' performance, was completed in 2018.[307]

Continuously operating reference stations

A key area of international cooperation has been the establishment of CORS in host countries to improve the accuracy of the BeiDou signal (see Figure 6). Press reports indicate that the PRC has established agreements with at least 15 countries to build CORS. Although information is lacking to provide a clear understanding of the extent of CORS construction internationally, a few countries do stand out. Uganda, for example, has built 30 CORS, and its network of CORS is described as the most advanced in East Africa.[308] According to a 2016 press report, as many as 40 CORS were planned to be built in Laos, including 6 in capital Vientiane.[309] However, how many stations have actually been built is unknown.

Figure 6. Reported international CORS sites or agreements



Sources: "People's Daily Published the Article Beidou Technology Promotes the Quality of China-Africa Cooperation"; "First BeiDou CORS Inaugurated in Laos"; Marjohn Sheikhi, "Chinese BeiDou BDS to Transfer Satellite Tech. to Iran," Mehr News Agency, Oct. 18, 2015, https://en.mehrnews.com/news/111132/Chinese-BeiDou-BDS-to-transfer-satellite-tech-to-Iran; "ComNav, CGEOS Build First BeiDou CORS Station in Europe," *GPS World*, Apr. 9, 2015, https://www.gpsworld.com/comnav-cgeos-build-first-BeiDou-cors-station-in-europe/; "First Beidou CORS Inaugurated in Laos," Lao News Agency, Sept. 21, 2016, https://kpl.gov.la/EN/detail.aspx?id=17337; Huapu Lu, ed., *Proceedings of the Second International Conference on Intelligent Transportation*, Singapore: Springer Science+Business Media, 2017; "About Us," Muya CORS, https://muya-cors.com/#about; Deng Xiaoci, "China, Arab States Ink New Action Plan Over BDS Cooperation," *Global* Times, Dec. 9, 2021, https://www.globaltimes.cn/page/202112/1241054.shtml; "SinoGNSS Devices Show Superior Performance in CORS Construction in Maldives," SinoGNSS. https://www.comnavtech.com/news/267.html; Deyana Goh, "China to Develop at Least 10 BeiDou Satellite Stations in Sri Lanka," Spacetech, Apr. 3, 2017, https://www.spacetechasia.com/china-to-develop-at-least-10-BeiDou-satellite-stations-in-sri-lanka/; "China's BeiDou System to Expand Cooperation to SE Asia."

MILITARY COOPERATION

Military cooperation on BeiDou falls into two categories: providing access to BeiDou's military signal and exporting weapons capable of receiving the BeiDou signal. Some countries may perceive GPS as a liability that exposes them to unwanted U.S. leverage and China as less likely to interfere with or shut down BeiDou's signal. Lacking access to GPS's military signal, some countries may also wish to incorporate the ostensibly less jammable BeiDou military signal into their domestic weapons development programs. Although it is unknown to what extent the

use of BeiDou in the guidance systems of exported PRC weapons is used as a selling point, BeiDou's use may be perceived as providing greater political and operational reliability. In some areas, BeiDou may provide better accuracies than GPS.

Potential access to BeiDou's military signal

Several reports have stated that Pakistan, Iran, and Saudi Arabia have entered into agreements with China on the military application of BeiDou.

Pakistan

The *New York Times* reported in 2018 that Pakistan had reached an agreement with the PRC for access to BeiDou's encrypted military signal.[310] According to press reporting attributed to *Defense News*, the Pakistani military understood that at that time the BeiDou system could not offer the same accuracy as GPS, but, according to one Pakistani air force pilot, "Pakistan's armed forces cannot rely on U.S. GPS because of its questionable availability during a conflict that has overtones of nuclear escalation."[311]

One press report states that the Pakistani military is moving to integrate its weapons and equipment with BeiDou.[312] BeiDou is reportedly used in Pakistan's Raad II cruise missile, Ababeel ballistic missile, and Babur cruise missiles. The JF-17 fighter jet, manufactured by China and flown by Pakistan, is reported to use BeiDou.[313]

Iran

In January 2021, Iran's ambassador to China announced that the PRC had given Iran access to BeiDou.[314] However, whether the Iranian ambassador was referring to BeiDou's military signal is unknown. At least as early as 2015, there were reports that the PRC was assisting Iran's military to integrate BeiDou capabilities into its domestically produced weapon systems. For instance, in October 2015, Iranian electronic defense company SAIran reportedly signed an agreement with PRC companies to integrate the BeiDou signal into weapons systems.[315] According to a report on the website of the PRC-based internet company NetEase, the use of BeiDou helped facilitate the Iranian seizure of a British tanker in 2020 when the U.S. military cut off GPS service to Iran. According to the article, the use of BeiDou forced the U.S. Navy to withdraw from the area.[316]

Saudi Arabia

China and Saudi Arabia held their first meeting in April 2017 to discuss BeiDou cooperation. Although that meeting did not mention military cooperation, a PRC press report notes that representatives from the PRC defense industry conglomerates China Aerospace Science and Technology Corporation, China North Industries, and China Electronics Technology Group attended the meeting.[317] The two countries reportedly agreed in March 2019 to "deepen military collaboration to jointly promote regional peace and stability."[318] This agreement was followed by an agreement on a draft memorandum of understanding signed on July 9, 2019, to cooperate on

the military use of BeiDou. The memorandum of understanding was signed by the Saudi Ministry of Defense and the PLA's Equipment Development Department.[319]

Precision-guided munition exports

BeiDou may also be used to increase PRC weapons exports. The PRC is the fourth largest arms exporter behind the United States, Russia, and France, with increasing arms sales to the Middle East and Africa. PRC arms exports are facilitated by their low cost, loose end user agreements, and quick approval process.

Missile and rocket exports

The PRC has exported ballistic missiles and rockets to Ethiopia, Myanmar, and Qatar that are reportedly equipped with GNSS guidance.

Ethiopia

Ethiopia has acquired the M20 ballistic missile, which can carry a 400-kilogram warhead at a range of at least 280 kilometers with a circular error probable of 30 meters. Ethiopia has also acquired the A200 multiple rocket launch system, which has 10 to 12 rockets (depending on the variant) with a range of 75 miles.[320]

Myanmar

In 2021, Myanmar displayed a transporter erector launcher (TEL) for an SY-400 (DF-12) ballistic missile. The SY-400 is reportedly guided by a GNSS that includes BeiDou.[321]

Qatar

In 2017, Qatar displayed a short-range ballistic missile system that appeared to be based on the SY-400 (TEL).[322]

UAVs

The PRC is the world's largest exporter of UAVs. The PRC has delivered 282 uncrewed combat aerial vehicles to 17 countries, compared to a total of 12 UAV exports by the United States. According to the U.S. Defense Department, the PRC has sold strike-capable Caihong or Wing Loong UAVs to Pakistan, Iraq, Saudi Arabia, Egypt, the United Arab Emirates, Algeria, Serbia, Indonesia, and Kazakhstan.[323]

Some of these deals appear to be significant. Saudi Arabia and China agreed in March 2017—one month before the first meeting between China and Saudi Arabia on BeiDou—to build a factory to manufacture the CH-4 UAV, a drone similar to the U.S. Air Force's General Atomics MQ-1 Predator.[324] In 2017, Saudi media reported that the Saudi government had reached an agreement with the PRC government for the purchase of 300 Wing Loong II UAVs worth approximately $10 billion.[325] In March 2022, the PRC and Saudi governments announced a joint venture between the Saudi company Advanced Communications and Electronics Systems and

China Electronics Technology Group Corporation to research and develop payload systems for UAVs, such as communications units, flight control units, camera systems, radar systems, and wireless detection systems.[326]

POLAR REGIONS

The Arctic

The PRC has stated the intention to become a "great polar power" by 2030 and sees the Arctic as important to achieving its goals of sustaining economic development; defending national sovereignty, security, and development interests; and reforming the global system to align with PRC interests.[327] The PRC has called itself a "Near-Arctic State" and states that the changes in the Arctic brought about by climate change and the melting of the polar ice sheet have a "vital bearing" on its national interests. The PRC has stated intentions to build a "Polar Silk Road" by establishing shipping routes through the Arctic that can shave weeks off travel time to Europe and to exploit the Arctic for its natural resources.[328] According to the U.S. government, "over the last decade, the PRC has doubled its investments, with a focus on critical mineral extraction; expanded its scientific activities; and used these scientific engagements to conduct dual-use research with intelligence or military applications in the Arctic."[329]

The PRC has taken actions to improve BeiDou's coverage in the Arctic, likely to support the achievement of these policy goals. In 2004, the PRC established the Yellow River research station in Ny-Ålesund, Norway, and in 2016, the PLA rebuilt the station and upgraded the station's BeiDou CORS.[330] In 2019, the PRC Ministry of Transport's Beihai Maritime Support Center performed tests to evaluate the ability of domestic shortwave radios and BeiDou's PNT and communication signals to support PRC vessels traversing the Arctic's Northeast Passage.[331] In 2017, PRC entities announced the launch of a satellite ground station in Nuuk, the capital of Greenland. The launch ceremony was attended by Zhao Yaosheng, a retired military officer who was an engineer on the BeiDou program and a former CEO of BDStar Navigation, discussed previously.[332] The construction of the station was canceled because the Greenland government had never given approval for the project.[333]

Antarctica

According to the U.S. Defense Department,

> The PRC is also increasing its presence in the Antarctic through scientific projects, commercial ventures, and infrastructure and capability investments, likely intended to strengthen its position for future claims to natural resources and maritime access. The PRC's strategy for Antarctica includes the use of dual-use technologies, facilities, and scientific research, which are likely intended, at least in part, to improve PLA capabilities.[334]

The PRC operates four scientific research stations in Antarctica and is building a fifth. Of those stations, at least two—Great Wall and Zhongshan—are acknowledged to have BeiDou reference stations.[335] BeiDou CORS improve the accuracy of the positioning and navigation signal for ships, aircraft, and vehicles traveling in the Antarctic region; the mapping of Antarctica; and the geolocation of mineral resources.[336] BeiDou is also likely valued for its SMS function. According to a PRC report on polar policy, satellite receiving and processing stations are "invaluable for 'preparing for the facilitation or interference of precision missile strikes and for targeting and communicating with various satellite systems.'"[337]

STANDARDS

The PRC government has also worked to have BeiDou ratified by international standardization bodies such as the ICAO, the IMO, the International Mobile Communications Partnership Project, and the International Satellite System for Search and Rescue (Cospas-Sarsat). Recognition by international bodies serves to expand the use of BeiDou internationally and enhance PRC national prestige by positioning it as a leader in these venues.

International Maritime Organization

The IMO is a United Nations organization responsible for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. According to its website,

> IMO is the global standard-setting authority for the safety, security and environmental performance of international shipping. Its main role is to create a regulatory framework for the shipping industry that is fair and effective, universally adopted and universally implemented.[338]

In November 2014, BeiDou became the third system to be recognized by IMO as a component of the World-Wide Radionavigation System.[339] The recognition allowed BeiDou receivers, in addition to GPS and GLONASS receivers, to be used by shipping companies for navigation.[340]

In November 2022, the IMO recognized BeiDou SMS for use in the Global Maritime Distress and Safety System (GMDSS). The decision broke the monopoly of Britain's Inmarsat and allowed the U.S.-based Iridium to be used in the GMDSS.[341] The recognition, however, was limited to areas surrounding China.[342]

International Civil Aviation Organization

The ICAO is a multinational organization composed of 193 national governments to support diplomacy and cooperation in air transportation.[343] In November 2020, BeiDou passed ICAO technical verifications, indicating that the BeiDou 3 global system's ability to provide services for global civil aviation had been internationally recognized.[344]

International Electrotechnical Commission

In 2020, the International Electrotechnical Commission released the first international standard for the testing of BeiDou shipborne receiving equipment, which specified the minimum performance requirements, methods of testing, and required test results for BeiDou shipborne receiver equipment when using BeiDou signals to determine position.[345]

International Cospas-Sarsat Programme

The International Cospas-Sarsat Programme "provides accurate, timely, and reliable distress alert and location data to help search and rescue authorities assist persons in distress." According to the organization's website,

> Cospas-Sarsat participants implement, maintain, co-ordinate and operate a satellite system capable of detecting distress alert transmissions from radio beacons that comply with Cospas-Sarsat specifications and performance standards, and of determining their position anywhere on the globe.[346]

BeiDou joined the program in 2017 in a move described by the PRC Ministry of Transport as enhancing "BeiDou's global capability to search for and rescue people in distress, showing China has carried out its responsibilities in global humanitarianism in accordance with international conventions."[347]

INTEROPERABILITY AND COMPATIBILITY

Interoperability and compatibility allow users to receive and use signals from different satellite navigation systems. Interoperability of PNT systems is defined by the U.S. government as the "ability of multiple, independent PNT services and their augmentations to be used together to provide better capabilities at the user level than would be achieved by relying solely on a single service or signal."[348] Compatibility is defined by the U.S. government as the "ability of multiple, independent PNT services and their augmentations to be used separately or in combination with each other without interfering with any individual service."[349]

The PRC government has sought interoperability and compatibility with other satellite navigation systems. According to one PRC official, "BeiDou is devoted to pursue compatibility and interoperability with other navigation satellite systems, and enable users to obtain better services."[350] PRC interoperability and compatibility agreements include the following:

- The U.S. and the PRC issued "Joint Statement on Civil Signal Compatibility and Interoperability Between the Global Positioning System (GPS) and the BeiDou Navigation Satellite System (BDS)" on December 4, 2017.[351] In 2020, the United States released a revised *National Space Policy* that declared that the United States will work to ensure compatibility with other GNSS providers but will seek interoperability with only "likeminded nations."[352]

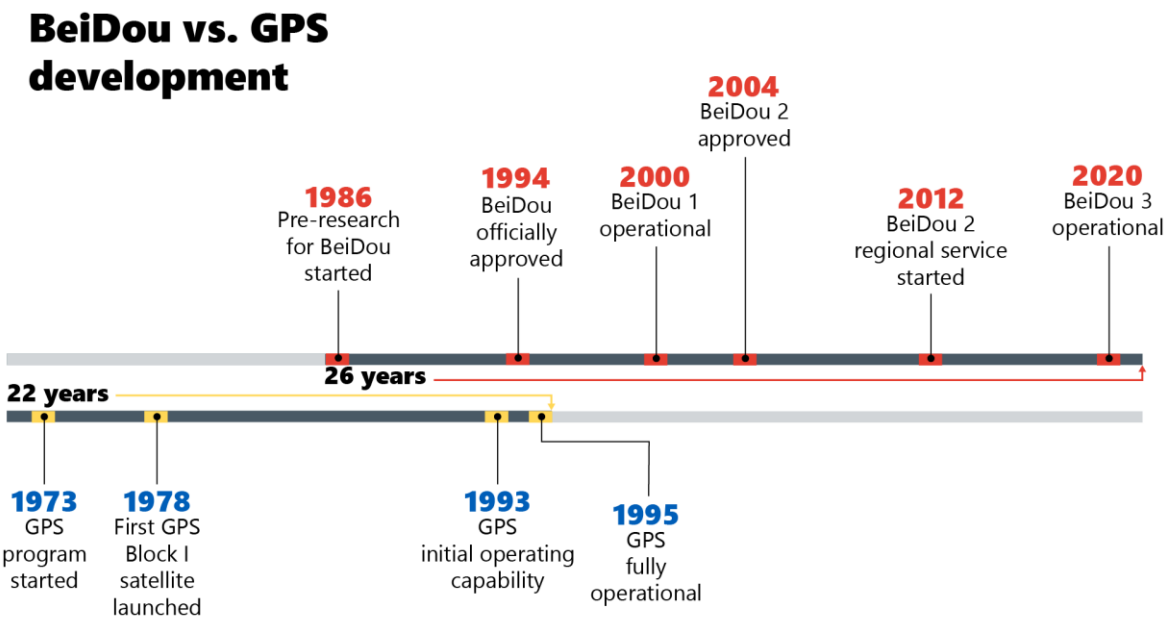
- The PRC and Russia signed an agreement on the interoperability and compatibility of BeiDou and GLONASS on August 31, 2019, as part of the Cooperative Agreement Between the PRC Government and the Russian Federation Government on the Peaceful Uses of BeiDou and GLONASS.[353]

CHAPTER 8: BEIDOU CLOSING THE GAP WITH GPS

The BeiDou program is an example of how the PRC uses state-directed measures to try to gain technological and market advantage in critical industrial sectors. This process identifies key technologies; provides policy, budgetary, and acquisition support for their development; and promotes market access. China's development of BeiDou also demonstrates the difficulty of controlling the spread of high technologies, especially in sectors in which the United States does not have exclusive control. As a result, the PRC has become a world leader in satellite-based PNT technologies despite strict U.S. export control laws, in part by acquiring key systems such as atomic clocks from other countries. Although the role of foreign technology in advancing BeiDou's development cannot be discounted, equally if not more important has been the commitment of the CCP to BeiDou and the commitment and ingenuity of the engineers responsible for its development.

The CCP's prioritization of BeiDou has resulted in similar RDA timelines as those of GPS (see Figure 7). The U.S. RDA process took just 22 years if taken from the GPS start date of 1973 to its full operation in 1995. It took 26 years for BeiDou to be completed if taken from official project initiation in 1994.

Figure 7. BeiDou and GPS RDA timelines



Source: CNA.

BeiDou is now closing the gap with GPS in terms of technology and acceptance. According to the China Satellite Navigation Association, in 2021, BeiDou had more than 2 billion users (the majority likely in China) and can provide navigation and positioning accuracies better than 9 meters and in some cases better than 5 meters, depending on location.[354] According to the *Nikkei Asian Review*, in 2019, even before BeiDou 3 had been completed, BeiDou satellites were observed more frequently than GPS satellites in 130 of 195 countries.[355]

Despite BeiDou's progress, GPS is still the world's GNSS of choice, with 4 billion users and an accuracy of 4.9 meters.[356] It also remains the primary system in almost all GNSS chips, meaning that the chips will first acquire GPS and then other systems.[357] Nevertheless, the BeiDou program has benefited from a latecomer advantage that has allowed it to benchmark the performance of GPS and add functionalities beyond those available with GPS. The PRC's latecomer advantage has also been aided by restraints put on GPS as a legacy system. In effect, the United States is a victim of its own success. The requirement to make new GPS satellites compatible with legacy satellites has slowed improvements to GPS, and the satellites' 12-year designed service life precludes their frequent replacement.[358] For example, GPS is the last GNSS to incorporate a search and rescue payload.[359]

GPS modernization is not standing still, however. In 2018, the Air Force signed a contract for 22 third-generation GPS III satellites that are 3 times more accurate and 8 times more resistant to jamming than GPS II satellites.[360] In January 2023, the Space Force launched the fifth GPS III satellite and plans to begin launching the even-more-improved GPS IIIF satellites in 2026.[361]

GPS IIIF satellites will be even more capable, with new payloads, although most of these upgrades will benefit the U.S. military. These upgrades include a redesigned Nuclear Detonation Detection System, Laser Retroreflector Arrays, a Cospas-Sarsat Search and Rescue payload, and an Energetic Charged Particles sensor. GPS IIIF also provides Precise Positioning Service to military operations. GPS IIIF satellites will also be compatible with the EU's Galileo and Japan's QZSS, allowing a common signal to be broadcast by up to 60 satellites, further enhancing accuracy and availability.[362]

Unfortunately, the development of GPS IIIF satellites has been criticized as being too slow, and the full constellation of GPS IIIF satellites will not be available until 2033.[363] A June 2023 Government Accountability Office (GAO) report, for example, noted that the modernization of GPS with a more jam-resistant military-specific signal known as the M-code has taken more than 20 years—about the same time it has taken China to operationalize its 45-satellite BeiDou constellation. The GAO also found that the Space Force would be unable to maintain 27 M-code capable satellites in orbit to meet certain user requirements for accuracy.[364]

Although BeiDou offers more functionality than GPS, this functionality may not necessarily translate into a consequential competitive edge (see Table 9). In some cases, GPS's

role as a basic technology has allowed developers to create applications that offer similar services as BeiDou when paired with GPS. Dedicated communications satellites, for example, may be able to provide better capabilities than BeiDou's SMS feature.

Table 9. Comparison of BeiDou and GPS features

BeiDou	GPS
Short messaging service. BeiDou's SMS function provides connectivity where cell phone coverage is lacking or while users are abroad without the need to change SIM cards. This feature could be especially attractive in the developing world in areas that are remote or where cell phone coverage is underserved or unserved. One day before Apple announced its Emergency SOS Function, PRC-based Huawei announced that its Mate 50 cell phone supports the BeiDou SMS for all types of communication, not just emergency notifications.	Communication satellites can also provide similar services. In November 2022, Apple announced that the iPhone 14 provides an Emergency SOS function via satellite to allow users to send text messages to emergency services. In August 2022, Starlink operator SpaceX and U.S. mobile communications provider T-Mobile announced an agreement for space-to-ground service, and in March 2023, the U.S. Federal Communications Commission proposed "a new regulatory framework to facilitate innovative collaborations between satellite operators and wireless companies."
Satellites in GEO. BeiDou satellites in GEO and IGSO mitigate the degradation of the BeiDou signal in urban and mountainous areas, also known as the "urban canyon effect." This feature allows the BeiDou signal to be more easily received in dense urban areas that are characteristic of megacities (cities with a population of more than 10 million), nearly all of which are in Belt and Road Initiative countries.	All GPS satellites are in MEO and there appear to be no plans for future generations of GPS satellites to be placed in GEO. Compatibility with Japan's QZSS and the future Korean Positioning System will help mitigate the urban canyon effect in the large cities of these allies. These systems would not extend coverage to other areas of Asia, the Middle East, and Africa, however.
Ground-based augmentation. The establishment of CORS across China and abroad allows BeiDou users to receive signals with decimeter-level accuracy. The BeiDou program intends for future generations of BeiDou to provide centimeter-level positioning.	The U.S. also has a network of nearly 2,000 CORS around the country operated by various government, academic, and private organizations. The network is coordinated by the National Oceanic and Atmospheric Administration.
Satellite-based augmentation. Satellite-based augmentation is accomplished with the use of BeiDou satellites.	The U.S. Federal Aviation Administration operates the Wide Area Augmentation System, which operates similarly to the BeiDou system but uses of a separate set of satellites working in conjunction with GPS.
International search and rescue service. BeiDou provides an international search and rescue service that allows users in distress to send and receive messages.	GPS IIIF satellites will offer an international search and rescue service and will begin to be launched in 2026.

BeiDou	GPS
Intersatellite links. Intersatellite links establish communications among BeiDou satellites so that instructions sent to one satellite can be sent to other satellites. This feature improves the "timeliness of satellite orbit and health information with less reliance on (ground) uplink stations." The use of intersatellite links is especially important for BeiDou because it helps overcome the PRC's lack of global ground stations.	GPS is not equipped with intersatellite links. Although the U.S. has more ground stations than the PRC to provide updates more frequently, the use of intersatellite links allow more frequent updates and better accuracies.
Laser retroreflector arrays. BeiDou satellites are equipped with laser retroreflector arrays that can accurately determine the position of satellites in orbit with millimeter accuracy. Knowing the precise orbit of a satellite can be used to provide better navigation and positioning accuracy.	GPS IIIF will be equipped with laser retroreflector arrays and will begin to be launched in 2026.
Precise point positioning. BeiDou's precise point positioning service can offer accuracies in the decimeter range. BeiDou's precise point positioning feature is only offered in China and surrounding areas.	Precise point positioning applications using GPS have been developed by commercial providers and are widely available. GPS IIIF satellites will offer precise point positioning to military operations.
Future capability. LEO satellites. The addition of a BeiDou LEO satellite navigation constellation beginning in 2025 promises to boost the satellite navigation signal, making it more accurate, more reliable, and less susceptible to jamming.	There are no plans for GPS to incorporate LEO satellites. Commercial providers are considering LEO constellations for navigation and positioning.

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CHAPTER 9: CONCLUSIONS AND IMPLICATIONS

The United States and China are in an emerging competition over satellite-based PNT. After 26 years of development, the PRC completed BeiDou in 2020 and is now working to improve the system to make it more accurate, to integrate it into global infrastructures, and to expand its use into new domains. Ultimately, the PRC intends to make BeiDou a ubiquitous and secure system that can surpass GPS in terms of technological capability and commercial acceptance.

Despite PRC recriminations over U.S. measures to decouple from the PRC, BeiDou's history demonstrates that the PRC has sought to achieve technological independence from the United States in key technologies. Seeking to reduce U.S. leverage over China, the CCP realized the significance of satellite-based PNT to modern warfare and developed BeiDou as an independent capability separate from GPS. Later, as satellite-based PNT began to undergird the functions of the high-tech economy, the CCP designated BeiDou as a part of its national infrastructure and removed the use of GPS in critical sectors such as electrical power generation, finance, and communications.

Loss of U.S. leadership in PNT could challenge the ability of the U.S. military to achieve dominance in a conflict with the PRC, lead to the loss of international influence for the United States, and expand market opportunities for PRC commerce.[365] In this chapter, we offer some concluding thoughts on implications for the United States.

BEIDOU AS AN INSTRUMENT OF PRC NATIONAL POWER

BeiDou's dual-use capabilities provide benefits to the PRC and present challenges to the U.S. across the four instruments of national power: diplomatic, information, military, and economic (DIME).

Diplomatic and information

The BeiDou program is one element of the PRC's foreign policy goal of reshaping the international system to better serve its national interests.

BeiDou likely improves the reputation of the CCP domestically and the PRC internationally. The CCP can claim that the successful completion of BeiDou demonstrates the superiority of "socialism with Chinese characteristics" and helps legitimize the CCP's authoritarian governance model. In a departure from usual practice, the final launch completing the BeiDou 3 constellation was announced in advance and broadcast live on China Central Television. Previously, BeiDou launches were acknowledged only after the satellites successfully achieved orbit.[366]

BeiDou also plays a role in improving China's relations with the developing world, especially with countries participating in the Belt and Road Initiative. China promotes BeiDou as

a tool to grow developing countries' economies and advance their S&T. In doing so, BeiDou could be perceived as an alternative to GPS for countries that may feel threatened by the United States or less inclined to view the United States favorably. Similar to China's own desire to achieve independence in satellite-based navigation, some countries may choose to adopt BeiDou to lessen the leverage that they believe their dependence on GPS provides to the United States. The adoption of BeiDou by countries other than China may also diminish U.S. status and influence. In 2021, for example, Iran's ambassador to China commented that BeiDou's completion was the "end to the monopoly of the U.S.'s GPS."[367]

PRC activities appear to be most extensive in the Arab world. The proclamation by Xi Jinping of a "Bring BeiDou to the Arab World" project indicates the importance of Arab countries to the PRC's international efforts and the promotion of BeiDou. PRC cooperation with Saudi Arabia appears to be particularly strong and seems tied to the economic and military agendas of the country.

Military and security

BeiDou's PNT and communications functions provide part of the fundamental architecture for carrying out the PLA's core operational concept of Multi-Domain Precision Warfare.

According to the Defense Department, MDPW is intended to leverage a C4ISR network that incorporates AI and big data to conduct joint strikes against key adversary vulnerabilities.[368] BeiDou plays an indispensable role in enabling precision strike, the movement of forces, communications, and situational awareness.

PRC media reporting and academic articles on BeiDou indicate that the PLA is using or is researching the application of BeiDou across the full range of military activities, including warfighting, border defense, logistics, and mobilization. The availability of BeiDou has also allowed the PLA and PLA researchers to think more deeply about how to further embed BeiDou into PLA operations to make the PLA a fully "informatized force," including the use of BeiDou for undersea and deep space navigation.

PRC media reporting and academic articles on BeiDou also indicate that BeiDou's SMS function is a critical, albeit secondary, capability whose importance should not be discounted. It enables communication between units, the cueing of cruise missiles, and the creation of GIS.

The completion and improvement of BeiDou provides numerous benefits to the PLA. The ability to rely on a PRC-owned and -operated GNSS could provide the PRC more freedom of action to use force or threaten the use of force. The PLA, for example, may be more likely to attack the GPS signal knowing that it can rely on BeiDou. The PLA has reportedly set up GPS jammers on its manmade islands in the South China Sea, and GPS spoofing episodes in Shanghai have caused concern that the PLA is testing a new electronic warfare method to counter GPS.[369] The

ability to accurately strike targets may also lessen the risk of offensive action and make it more likely that the PRC would use force.

The use of BeiDou in precision strike, to guide uncrewed vehicles, and to support enabling functions such as logistics will enhance PLA efforts to deter the actions of potential adversaries and to effectively carry out strike operations if deterrence fails. In addition, BeiDou's global coverage will better enable the PLA to operate and conduct strikes globally, especially in the Western Pacific, South Asia, the Middle East, and Africa. Conversely, the increased capabilities that BeiDou provides to the PLA could mean that efforts to deter PRC military actions will be less effective.

BeiDou will allow the PLA to better exploit the benefits of AI and autonomy.

In 2017, Xi Jinping called on the PLA to "accelerate the development of military intelligentization"—PLA speak for warfare that stresses the use of AI and autonomous weapon systems.[370] BeiDou's PNT functions will allow autonomous systems to guide themselves more securely and independently, and its SMS function could be used to issue commands to autonomous vehicles and enable autonomous vehicles to communicate among themselves in self-organizing swarm operations.

Use of BeiDou in critical infrastructure could increase dependency on PRC.

Although it is unlikely that any country will rely solely on BeiDou for its satellite-based PNT needs, the path dependencies created by countries adopting BeiDou as their primary GNSS for finance, electrical power generation, and communications infrastructure and by the PRC export of smart cities technologies could expose countries to PRC leverage if the PRC were to deny or degrade the BeiDou signal.

BeiDou will increase PRC surveillance concerns.

The PRC's ability to monitor the movement and communications of those using BeiDou's SMS function increases PRC surveillance concerns. Although people can be tracked by their cell phone usage without using BeiDou, because BeiDou is operated by the PLA, the opportunities for espionage with BeiDou are much greater than for those systems operated by private corporations.

Economic

BeiDou is intended to replace GPS and U.S. companies as the dominant market player.

Economic forces will not bring about the demise of the U.S. government–operated GPS. PRC mercantilist policies, however, can affect downstream actors that develop satellite navigation devices and applications. Although satellite navigation products and services can use signals from multiple systems, PRC mercantilist policies could help expand the popularity of devices and services manufactured and provided by PRC companies. This issue could be especially prominent in cell phone applications that use satellite navigation. An expansion of PRC companies providing

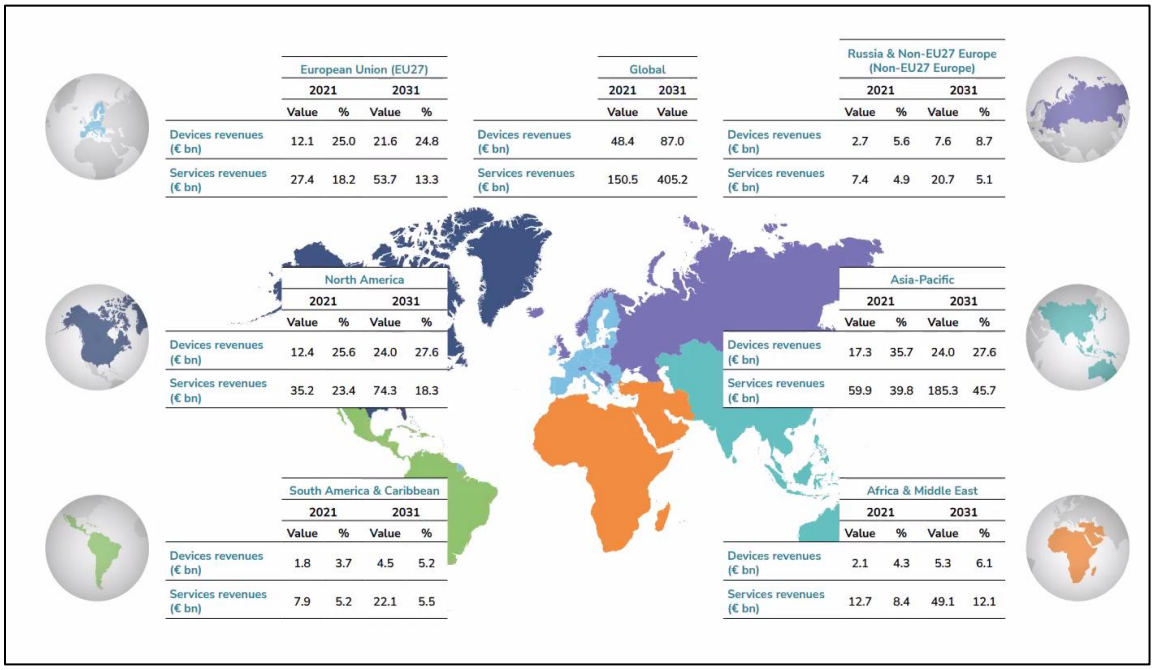
satellite navigation products and services will likely mean a drop in market share for non-PRC companies, many of which are U.S. companies.[371]

The popularity of BeiDou may increase with the spread of CORS. Although the CORS that China is setting up in foreign countries reportedly can receive signals from multiple GNSS, highly accurate positioning and navigation information achieved through the expansion of CORS across the PRC and other countries could promote the use of BeiDou for vehicle navigation. Such information is intended to promote the use of self-driving cars and other autonomous vehicles that could promote the sales of PRC automotives internationally. Indeed, lane-level navigation using BeiDou is now being piloted in several PRC cities. The more aggressive testing and adoption of autonomous vehicles of all types using BeiDou could cause the PRC to become a leader in this sector. The use of high-accuracy services may also help improve traffic management, a major element of smart cities technologies, which in turn is a major element of China's Belt and Road Initiative, which envisions the ability to redistribute transportation flows around bottlenecks.[372]

PRC mercantilist policies may increase the use of BeiDou in the developing world.

The use of BeiDou devices and services in the U.S. will likely be limited by the dominance of U.S. companies, efforts to restrict the sale of PRC brands such as Huawei, and a ban on BeiDou CORS being set up in the United States. BeiDou's biggest economic effect will likely be in China and in countries participating in the Belt and Road Initiative, in which PRC outreach is intended to take advantage of the markets of 147 countries making up two-thirds of the world's population and 40 percent of the global GDP.[373] According to the European Union Agency for the Space Programme, the global market for GNSS devices and services will increase from €198.9 billion in 2021 to €492.2 billion in 2031 (see Figure 8). Most of this rise will come from the Asia-Pacific region (most likely China), which will increase from €77.2 billion in 2021 to €209.3 billion in 2031. The Middle East and Africa, however, will remain relatively small markets, with a total market of €54.4 billion in 2031. The United States and Canada, where GPS will likely remain dominant, will remain the second largest market at €98.3 billion in 2031.[374]

Figure 8. Global demand for GNSS devices and services, 2021 and 2031



Source: EU Space Programme, *EUSPA EO and GNSS Market Report*, p. 18.

PRC-sponsored training and education is intended to increase PRC global market share.

PRC government–sponsored education and training programs contain a marketing component that is intended to advance PRC commercial interests. Training conducted by employees of PRC companies can expose potential customers to PRC products and promote the perception that PRC companies are the provider of choice for satellite PNT solutions.

RECOMMENDATIONS

Add functionality to GPS to maintain U.S. technological lead in satellite navigation

The PRC plans to "gain a competitive edge" in satellite navigation by developing a "more extensive, more integrated, and more intelligent" BeiDou system that provides "flexible, smart, precise and secure navigation, positioning and timing services," which indicates that the PRC plans to upgrade BeiDou.[375] Although not all of BeiDou's capabilities, such as its SMS function, may need to be incorporated into GPS, the push by China to add functionality to BeiDou may create opportunities to surpass GPS. Technological improvements to GPS could include the following:

- Software-upgradable satellite architectures to allow software updates to drive improvements in GPS rather than hardware improvements, which require the launch of satellites.[376]
- The addition of high-accuracy services, such as internet-based high-accuracy services.[377]

- Intersatellite links to provide more frequent updates.[378]
- Expanding the GPS constellation to GEO and IGSO to mitigate the degradation of the GPS signal in large built-up urban areas.
- Expanding the GPS constellation to LEO to provide more accurate and reliable signals with less interference.

Develop diverse PNT solutions to provide mission assurance in the event GPS is degraded or denied

The Defense Department is developing technologies to complement GPS in the event that it is degraded or denied. These technologies include improved inertial sensors, chip-scale atomic clocks, celestial navigation, terrestrial image analysis, and magnetic navigation. None of these methods is as accurate as GPS, but when used in combination, they may provide sufficiently precise accuracies. However, according to a May 2021 GAO report, alternate PNT sources are not prioritized within the Defense Department.[379]

Promote GPS as an instrument of national power

The PNT competition between the United States and China means that the United States must consider not only how to best maintain its technological lead in PNT for military advantage but also how to compete with the PRC's efforts to promote BeiDou across the DIME. Strengthening the National Coordinating Office for Space-Based Positioning, Navigation, and Timing or establishing an organization at the White House Office of Science and Technology Policy to promote GPS as an instrument of national power—militarily, diplomatically, and commercially—could better help the United States meet the challenges of the satellite PNT competition that span across the DIME.

Conduct international GPS outreach

Establishing an office to conduct international training and education on satellite-based PNT with a subsidiary mission of promoting GPS and U.S. commercial interests could be one instrument for increasing U.S. influence and challenging the PRC narrative of providing a more advanced system and being a more reliable GNSS partner. However, whether there is a U.S. government agency well suited to conducting training and education is unclear. An alternative to a government-run approach would be to outsource the effort to U.S. companies, possibly using the Agency for International Development, the US Telecom Training Institute, or the International Development Finance Corporation.

FIGURES

TABLES

ABBREVIATIONS

AI	artificial intelligence
APSCO	Asia-Pacific Space Cooperation Organization
ASEAN	Association of Southeast Asian Nations
C4ISR	command, control, communications, computers, intelligence, surveillance, and reconnaissance
CAS	Chinese Academy of Sciences
CASIC	China Aerospace and Industry Corporation
CAST	China Academy of Space Technology
CCP	Chinese Communist Party
CMC	Central Military Commission
CNSO	China Navigation Satellite Office
CORS	continuously operating reference stations
DIME	diplomatic, information, military, and economic
EU	European Union
FYP	Five-Year Plan
GAO	Government Accountability Office
GBAS	ground-based augmentation stations
GEO	geosynchronous orbit
GIS	geographic information systems
GMDSS	Global Maritime Distress and Safety System
GNSS	global navigation satellite system
GPS	Global Positioning System
GSD	General Staff Department
ICAO	International Civil Aviation Organization
IDDS	Innovation Driven Development Strategy
IFF	identification friend or foe
IGSO	inclined geosynchronous orbit
IMO	International Maritime Organization
LEO	low Earth orbit
MDPW	Multi-Domain Precision Warfare
MEO	medium Earth orbit
MLP	National Medium and Long-Term Development Plan for Satellite Navigation
NavIC	Navigation with India Constellation
PLA	People's Liberation Army

PLAAF	People’s Liberation Army Air Force
PLAN	People’s Liberation Army Navy
PNT	positioning, navigation, and timing
PRC	People’s Republic of China
QZSS	Quasi-Zenith Satellite System
R&D	research and development
RDA	research, development, and acquisition
RDSS	radio determination satellite service
S&T	science and technology
SMS	short messaging service
TEL	transporter erector launcher
UAV	unmanned aerial vehicle

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